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BY
Mostafa MEHRTASH

PERFORMANCE EVALUATION OF SOLAR TRACKING PHOTOVOLTAIC
SYSTEMS OPERATING IN CANADA

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PERFROMANCE EVALUATION OF SOLAR TRACKING PHOTOVOLTAIC SYSTEMS OPERATING IN CANADA

Mostafa MEHRTASH

RÉSUMÉ

En 2011, la capacité totale installée du Photovoltaïque au Canada était de 289 MW et elle pourrait atteindre entre 9 et 15 GW d'ici 2025. Selon des études antérieures, des systèmes de suivi solaires PV peuvent capturer 20% à 50% plus de rayonnement solaire que les systèmes fixes. Un suiveur solaire est un dispositif qui maintient les panneaux photovoltaïques perpendiculaires aux rayons du soleil. Il y a un manque de connaissances sur la performance des systèmes solaires photovoltaïques de suivi d'exploitation dans les conditions météorologiques sévères du Canada.

Trois objectifs principaux ont été définis pour cette recherche. Le premier objectif est l'évaluation des performances en fonction de la stratégie de suivi pour les systèmes PV. Cet objectif est atteint par la simulation et l'analyse de quatre systèmes PV: horizontal fixe, incliné fixe, suivi selon un axe et suivi selon deux axes. Ces systèmes sont analysés au cours des périodes annuelles, mensuelles et journalières. Quatre villes avec des conditions météorologiques différentes ont été étudiées: Montréal (Canada), Casablanca (Maroc), Ouagadougou (Burkina Faso), et Olympia (USA). Les résultats obtenus à partir de simulations montrent que les systèmes de suivi selon deux axes présentent les rendements les plus élevés dans tous les endroits choisis.

Le deuxième objectif est de déterminer l'orientation optimale d'un système d'exploitation PV dans des conditions climatiques du Canada. Cet objectif est atteint en enquêtant sur la météo et les conditions environnementales du Canada qui touchent les systèmes PV, y compris les basses températures en hiver et le rayonnement réfléchi par la neige (effet albédo). Le rayonnement réfléchi par la neige cumulée sur le sol entraîne une augmentation de

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l'irradiation des panneaux jusqu'à 4,1%, 5,6% et 6,9% pour les systèmes inclinés, avec suivi selon un axe, et avec suivi selon deux axes pendant l'hiver, respectivement. Les systèmes de suivis selon un axe et deux axes reçoivent 28% et 33% de plus de rayonnement solaire que le système incliné sur un an. De plus, le suivi du soleil pourrait précipiter le phénomène de fusion de la glace et de la neige accumulée sur les panneaux photovoltaïques.

L'objectif final de cette thèse est le choix de la méthode de suivi optimale pour le Canada. Cet objectif est atteint par l'analyse de diverses orientations des systèmes PV dans les jours typiques: une journée d'hiver claire, une claire journée d'été, et une journée nuageuse d'hiver et d'été.

Selon les analyses quotidiennes, le suivi du soleil est efficace les jours de soleil direct (clairs), contre-productif les jours nuageux, et dépend de l'indice de clarté dans les jours très nuageux. Ces résultats sont corroborés par des recherches antérieures. Les résultats permettent de proposer une méthode qui permet de suivre le soleil dans des conditions claires et d'aller à la position horizontale dans des conditions nuageuses. En conditions nuageuses partielles, la stratégie de suivi à adopter dépend de l'indice de clarté et de rayonnement réfléchi par le sol.

Mots-clés : énergie solaire, photovoltaïque, suivi solaire, performance, albedo.

PERFORMANCE EVALUATION OF SOLAR TRACKING PHOTOVOLTAIC SYSTEMS OPERATING IN CANADA

Mostafa MEHRTASH

ABSTRACT

In 2011, the total installed PV capacity in Canada was almost 289 MW and it could reach between 9 and 15 GW by 2025. According to previous studies, sun tracking PV systems can capture 20% to 50% more solar radiation than fixed systems. Solar tracker is a device that keeps PV panels perpendicular to the sun rays. There is a lack of knowledge about the performance of sun tracking PV systems operating under weather conditions of Canada.

Three principal objectives were defined for this research. The first objective is the performance evaluation of various configurations (fixed and tracking) of PV systems. This objective is achieved by simulation and analysis of four orientations of PV systems: horizontal, inclined, single-axis tracking, and dual-axis tracking systems. These systems are analysed in yearly and daily periods. Four cities with different typical weather conditions have been studied: Montreal (Canada), Casablanca (Morocco), Ouagadougou (Burkina Faso), and Olympia (U.S.A). The results from simulations show that the dual-axis tracking PV systems have the best performance in all selected locations.

The second objective is the investigation of environmental effects on the performance of PV systems. This objective is achieved by studying the ambient temperature and reflected radiation from the snow (albedo effect) influences. Reflected radiation from the snow accumulated on the ground causes an increase in arrays irradiation up to 4.1%, 5.6%, and 6.9% for tilted, single-axis tracking, and dual-axis tracking systems over the winter, respectively.

The final objective of this thesis is developing the optimum tracking method for Canada. This objective is achieved by analyzing various orientations of PV systems in some typical

days: a clear winter day, a clear summer day, an overcast day for both winter and summer, and calculation of tracking advantage during these days.

According to the daily analyses, tracking the sun is effective in clear days and unnecessary in overcast days. These results are supported by previous researches. Our results allow proposing a method that tracks the sun in clear conditions and go to horizontal position in overcast conditions. In partially cloudy conditions, depending on the clearness index and reflected radiation from the ground, tracking the sun could be effective or counterproductive. Furthermore, going to horizontal position consumes energy. If the reflected radiation from the snow is considerable, the PV system should stay in final position as it doesn't consume any energy.

Keywords: solar energy, photovoltaic, solar tracking, performance, albedo.

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ABBREVIATIONS AND ACRONYMS

PV	Photovoltaic
TW	Terawatt
TWh	Terawatt hour
GW	Gigawatt
MW	Megawatt
kWh	Kilowatt hour
kW	Kilowatt
FIT	Feed in tariff
OPA	Ontario power authority
USA	United States of America
μm	Micrometer
H ₂ O	Water
CO ₂	Carbon dioxide
LST	Local solar time
MSESC	Maui Solar Energy Software Corporation
HDKR	Hay-Davies-Klucher-Reindl
TMY2	Typical meteorological year 2
TMY3	Typical meteorological year 3
SAM	System advisor model
NREL	National renewable energy laboratory
SNL	Sandia national laboratory
TRNSYS	Transient system simulation tool
EPW	Energy plus weather
ISM	Swiss Institute for Meteorology
EMPA	Eidgenössische Materialprüfung- und Forschungsanstalt
NASA	National aeronautics and space administration
SSE	Solar system exploration
WRDC	World radiation data centre

PVGIS	Photovoltaic geographical information system
3-D	Three dimensional
STC	Standard test condition
SWERA	Solar and wind energy assessment
PLC	Programmable logic controller
I-V	Current-voltage
DTS	Direct toward sun
LDR	Light dependent resistive
RS232	Recommended standard 232
TA	Tracking advantage
GI	Global irradiance
GHI	Global horizontal irradiance
DHI	Diffuse horizontal irradiance
USD	United States dollar
CPC	Compound parabolic concentrator
AC	Alternative current
DC	Direct current
T	Tilted
DT	Dual-axis tracking
ST	Single-axis tracking
H	Horizontal
DT-H	Dual-axis tracking versus horizontal
ST-H	Single-axis tracking versus horizontal
DT-T	Dual-axis tracking versus tilted
ST-T	Single-axis tracking versus tilted
DT-ST	Dual-axis tracking versus single-axis tracking
CanSIA	the Canadian Solar Industries Association

SYMBOLS

I	hourly radiation (w/m^2)
n	day number
φ	Latitude angle ($^\circ$)
δ	declination angle ($^\circ$)
ω	hour angle ($^\circ$)
R	geometric factor
θ	incidence angle ($^\circ$)
θ_z	zenith angle ($^\circ$)
β	surface slope ($^\circ$)
γ	surface azimuth angle ($^\circ$)
ρ_g	ground reflection coefficient
A_i	anisotropic index
α_s	solar altitude angle ($^\circ$)
γ_s	solar azimuth angle ($^\circ$)
C_a	additional cost (USD)
P_v	power (W)
A	ampere
V	volt

Subscripts

on	extraterrestrial
sc	solar constant
T	total
b	Beam (direct)
d	diffused
refl	reflected
o	Extraterrestrial upon a horizontal surface

INTRODUCTION

In recent decades, energy has become a significant issue in the world. Fossil fuel resources are decreasing while the world energy consumption is increasing considerably. Moreover, the consumption of fossil fuels causes air pollution. An obvious solution for energy and air pollution problems is the employment of renewable energies like solar, wind, geothermal, etc. Solar energy has the largest potential among all renewable energy resources. The average available solar power resource on earth's surface is 36000 billion watts (3.6×10^4 TW_{ave}) when the wind power resource is 72 TW_{ave}, geothermal power resource is 9.7 TW_{ave}, and the human power use is 15 TW_{ave} (Archer and Jacobson, 2005). The incident solar radiation upon dry surfaces of the earth could supply 1900 times the world energy consumption (Sick, 1996). Today, solar energy is captured essentially by photovoltaic (PV) modules and solar thermal collectors. The work presented here concerns the first type of solar energy converters: Photovoltaic (PV) modules. Such modules convert the solar radiation into electricity. Since many years ago, this technology has been used as a source of energy for several small applications like calculators and watches. Although PV has been known since more than a hundred years, it evolved considerably as a renewable energy in recent years.

Canada status

Canada is a significant part of the global energy trade since it is the principal energy exporter to the United States, which is the largest energy consumer in the world. Canada exports crude oil, natural gas, coal, and electricity. Canada was placed in the first five biggest energy producing countries in the world in 2008 by producing 5600 TWh of primary energy, while its total energy consumption (primary and secondary) was 4111 TWh (Energy information administration, 2011). One of the largest hydroelectricity producers of the world is Canada. In 2008, it had 127.6 GW installed capacity of electricity generation by hydropower. 58% of generated electricity in Canada is produced by hydropower. In 2009, Canada produced 363.4 TWh in hydroelectricity and ranked third in the world. The capacity of hydroelectricity is 70,858 MW in Canada, while Quebec is the largest hydroelectricity producer in Canada with

more than the 50% of the capacity, and this is a renewable energy with conversion efficiency of 95%. (Ray, 2010; Centre for Energy, 2011; Energici, 2011).

PV potential in Canada

The potential for PV installation is generally expressed in terms of the ratio of total energy (recovered or incident) to the peak power at one location thus expressed in terms of kWh/kW. kWh stands for kilowatt hour, which is how many kilowatts are produced in one hour. kW stands for kilowatt peak, which is the power that a PV module can produce in the ideal conditions. This ideal condition is specified by a radiation intensity of 1000 W/m^2 , and a cell temperature of 25°C .

Annual average of PV potential for systems adjusted at latitude tilt angle ranges from 933 kWh/kW in St. John's, Newfoundland to 1361 kWh/kW in Regina, Saskatchewan (Figure 0.1). Even the minimum PV potential in Canada (Newfoundland) is larger than Tokyo's and Berlin's potential (885 kWh/kW and 848 kWh/kW, respectively) while Japan and Germany are among the world-leaders in PV. Moreover, the PV potential in Regina is larger than the potential of Sydney, Australia (1343 kWh/kW). Figure 0.1 shows the annual PV potential for latitude tilt angle in Canada. The southern part of Canada has a large PV potential in the range of 1000 to 1400 kWh/kW, while the northern parts do not have sufficient potential to take advantage from PV (Pelland, 2006).

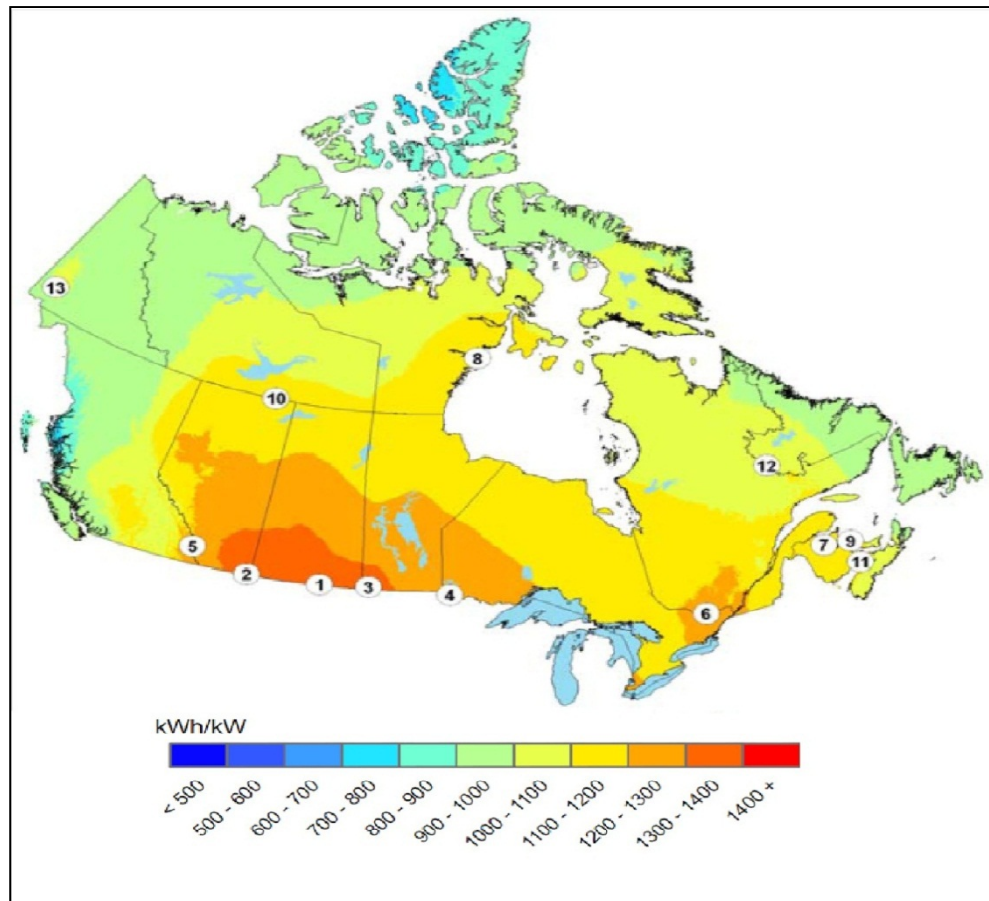


Figure 0.1 Yearly PV potential map (kWh/kW) for latitude tilt in Canada (Pelland, 2006)

Table 0.1 illustrates the annual PV potential of capital and major cities of the world. The interesting point is the position of Canadian cities. In contrast to popular belief, Canadian cities have a large PV potential as compared to other cities. For instance, Regina stands before Sydney, Australia and Rio de Janeiro, Brazil, the cities that are well known as sunny places. Berlin, where PV industry is very popular, has a smaller potential than Montreal with its northern climate.

Table 0.1 Yearly PV potential of capital and major cities of the world (Pelland, 2006)

City	Yearly PV potential (kWh/kW)
Cairo, Egypt	1635
Cape town, South Africa	1538
New Delhi, India	1523
Los Angeles, U.S.A	1485
Mexico city, Mexico	1425
<i>Regina, Saskatchewan</i>	1361
Sydney, Australia	1343
<i>Calgary, Alberta</i>	1292
Rome, Italy	1283
<i>Winnipeg, Manitoba</i>	1277
Rio de Janeiro, Brazil	1253
<i>Ottawa, Ontario</i>	1198
<i>Montreal, Quebec</i>	1185
<i>Toronto, Ontario</i>	1161
Beijing, China	1148
<i>Fredericton, New Brunswick</i>	1145
Washington, U.S.A	1133
<i>Charlottetown, Prince Edward Island</i>	1095
<i>Victoria, British Columbia</i>	1091
<i>Halifax, Nova Scotia</i>	1074
Paris, France	938
<i>St. John's, Newfoundland/Labrador</i>	933
Tokyo, Japan	885
Berlin, Germany	848
Moscow, Russia	803
London, England	728

Figure 0.2 shows the cumulative PV capacity in Canada from 1992 to 2009. The Canadian PV market is at early development steps as compared to other major markets but it has experienced a significant jump in 2009. Between 1992 and 2008, the annual growth of installed capacity was 30% approximately, while in 2009 it has jumped to 790%. The Ontario feed-in tariff (FIT) caused this major jump in growth of installed capacity (Ayob, 2011).

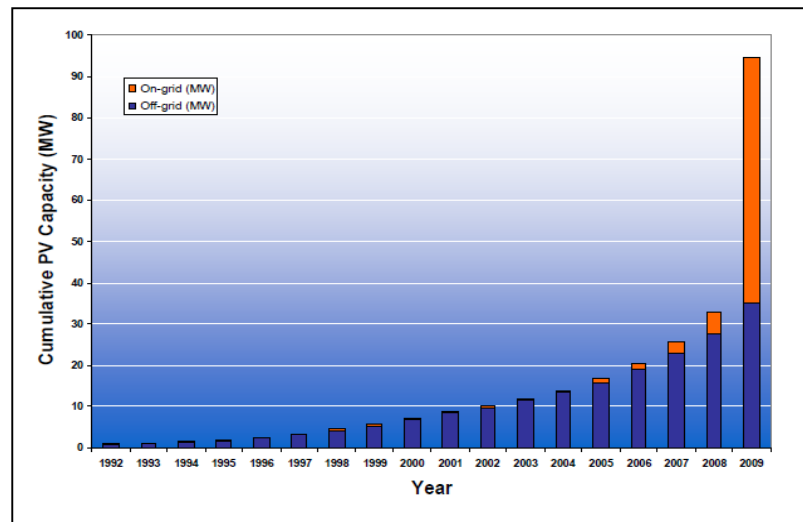


Figure 0.2 Cumulative PV capacity in Canada 1992-2009 (Ayob, 2011)

The province of Ontario is the PV investment leader in Canada. In 2010, the Ontario Ministry of Energy reaffirmed its commitment to maintain a modern, clean, and reliable electricity system. Due to having the Feed-in Tariff (FIT and micro-FIT) program, Ontario Power Authority (OPA) had 3352 MW of in-service generation capacity from renewable energies in 2010. 186 MW of PV systems were in service and another 1243 MW were under development. In 2010, Ontario had the largest PV power plant (Sarnia) in the world with 80 MW power, but in 2011 it became the third largest one after the China's and Ukraine's PV power plants (Dignard-Bailey, 2010).

Recently, optimization of PV systems (to produce more electricity) has become a significant challenge. The main research challenges in this field focus on improvement of PV cells

efficiency and optimization of PV systems orientations which will be discussed in this thesis. The captured solar radiation and electricity production of PV systems are very depending on environmental conditions. Canada has particularly severe weather conditions which justifies several researches in this field.

Research problem

Since sun tracking PV systems produce more electricity than fixed systems, several customers and companies in Canada are interested in this type of systems (CanSIA, 2010). Although solar trackers increase the modules irradiance recovery potential and electricity production of PV systems subsequently, they also increase the initial cost, the maintenance cost, and the complexity of the projects because of moving parts including motors and bearings. Moreover, the performance of sun tracking PV systems depends not only on the method of tracking, but also the local climate conditions of installed systems. Due to severe weather conditions of Canada, many environmental factors affect the performance of PV systems including frost, snow, freezing rain, very low temperatures, and reflected radiation from the snow (albedo effect) (Abdallah, 2004; Al-Mohamad, 2004; Gabler, 2005; Huang and Sun, 2007; Chang, 2009; Chang, 2009). Despite the importance of this subject, there is a lack of knowledge in energetic, economical, and environmental performances of sun tracking PV systems in Canada.

Objective

The objective of this research is to evaluate and investigate the performance of sun tracking PV systems in southern Canada. A secondary objective is to propose an optimal orientation for PV systems in this geographical location. Today, there are various methods to track the sun and control the tracker. Several algorithms are created to control the motion of trackers, a lot of information is essential to create an appropriate algorithm. The work presented here illustrates the optimum tracking method for PV systems operating in Canada with respect to its weather conditions.

Methodology

This study provides a theoretical evaluation of different configurations for PV systems in different locations. To this end, several simulations are carried out by PVSOL Pro. These simulations not only analyze the performance of PV systems, but also investigate the environmental effects. In order to investigate the environmental effects on performance of PV systems more precisely, four different locations with typical weather conditions have been selected, including Montreal (Canada), Casablanca (Morocco), Ouagadougou (Burkina Faso), and Olympia (U.S.A). They are classified as cold, mild, hot, and oceanic climate locations, respectively. The analyses have been done for daily and monthly periods.

Thesis organization

The introduction has already presented the energy problem and renewable energies as a solution. It also provided an overview of the energy status and PV potential of Canada. Finally, the research problem, objective, and methodology of this research were described briefly. Chapter 1 explains the background about solar radiation, radiation models, PV analysis softwares, and solar tracking systems. Chapter 2 presents a review of literature about sun tracking PV systems. Chapter 3 describes the simulations for Montreal, Casablanca, Ouagadougou, and Olympia. Then, it compares the results for the four locations and analyzes the environmental effects on PV systems. General conclusions are presented in the conclusion section. Finally, recommendations for future researches are formulated in the recommendation section to improve this field of study.

CHAPTER 1

BACKGROUND

Radiation is emitted from the sun over the whole spectrum, from gamma to radio waves. For the purpose of PV applications, solar radiation may be classified in two main ranges: short-wave radiation and long-wave radiation. Short-wave radiation wavelength range is between 0.3 to 3 μm . It originates directly from the sun and includes both direct and diffuse radiation. Long-wave radiation wavelength is larger than 3 μm . It is mostly created by atmosphere or any other sources at temperatures near ordinary ambient temperature (Duffie and Beckman, 1974). There are two main models to calculate the incident solar radiation on surfaces. A general overview of solar radiation and its models, PV analysis softwares, and sun trackers is presented herein.

1.1 Solar radiation

Solar radiation is scattered in atmosphere by air molecules, water, and dust. A part of solar radiation is also absorbed in atmosphere by O_3 , H_2O , and CO_2 . The solar radiation that passes through atmosphere directly to the earth is the direct solar radiation, and the scattered part of the radiation is called diffuse solar radiation. The direct and diffuse solar radiation incidents on a horizontal surface make up global solar irradiance. The annual available solar energy depends on the geographical position and meteorological conditions.

Table 1.1 Incident solar energy per unit area upon
a horizontal surface in different locations (Duffie and Beckman, 1974)

Location	Latitude	Annual incident energy (kWh/m^2)
Sahara	25°N	2500
Israel	33°N	2000
Trapani, Italy	38°N	1800
Freiburg, Germany	48°N	1100

Location	Latitude	Annual incident energy (kWh/m ²)
Helsinki, Finland	60°N	950
Lerwick, United Kingdom	60°N	775

Table 1.1 presents the incident solar energy upon a horizontal surface in different locations of the world (Duffie and Beckman, 1974). This table illustrates the relation between the latitude angle and the incident energy on horizontal surface. In low latitude locations the annual incident energy on a horizontal surface is considerably higher than in high latitude locations.

1.2 Sun's position in the sky

The sun's position in the sky can be described by several angles. These angles are indicated in Figure 1.1. In this figure, there is an inclined plane to show the relative angles between the sun and a tilted surface.

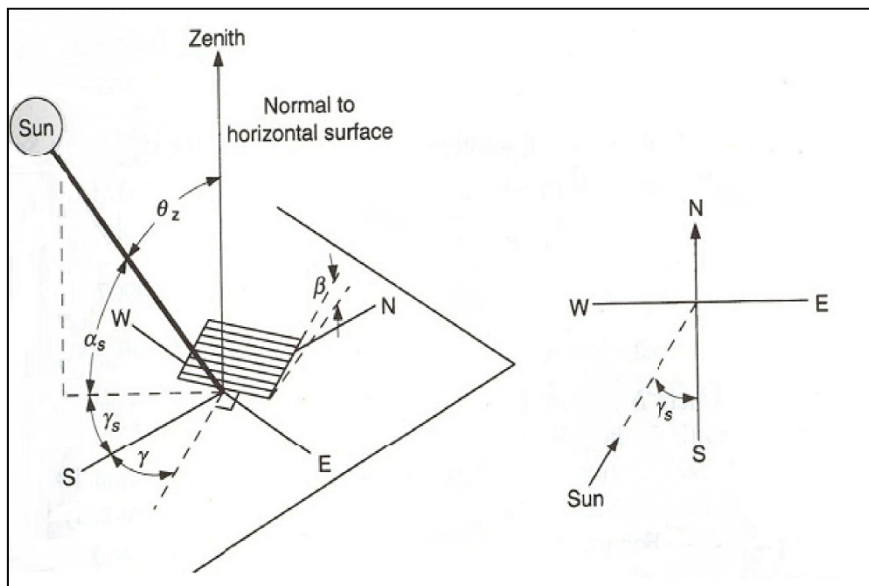


Figure 1.1 Sun's angles (Duffie and Beckman, 1974)

β is the slope of the plane from horizontal position. θ_z is the angle of incidence of direct radiation on a horizontal plane. It is the angle between vertical and the line to the sun and is

called zenith angle. The angle between horizon and sun's rays is called solar altitude angle (α_s) which illustrates the height of the sun in the sky. Solar azimuth angle (γ_s) is the angle between the south and the horizontal projection of direct radiation. Surface azimuth angle (γ) is the angle between the south direction and the direction where the plane is facing. In Figure 1.2 the solar position in the sky is shown for latitude of $\pm 45^\circ$. Solar altitude angle and azimuth angle are indicated in the plot by dates and times. As it can be seen, height of the sun reaches its minimum amount in December and maximum amount in June (Duffie and Beckman, 1974).

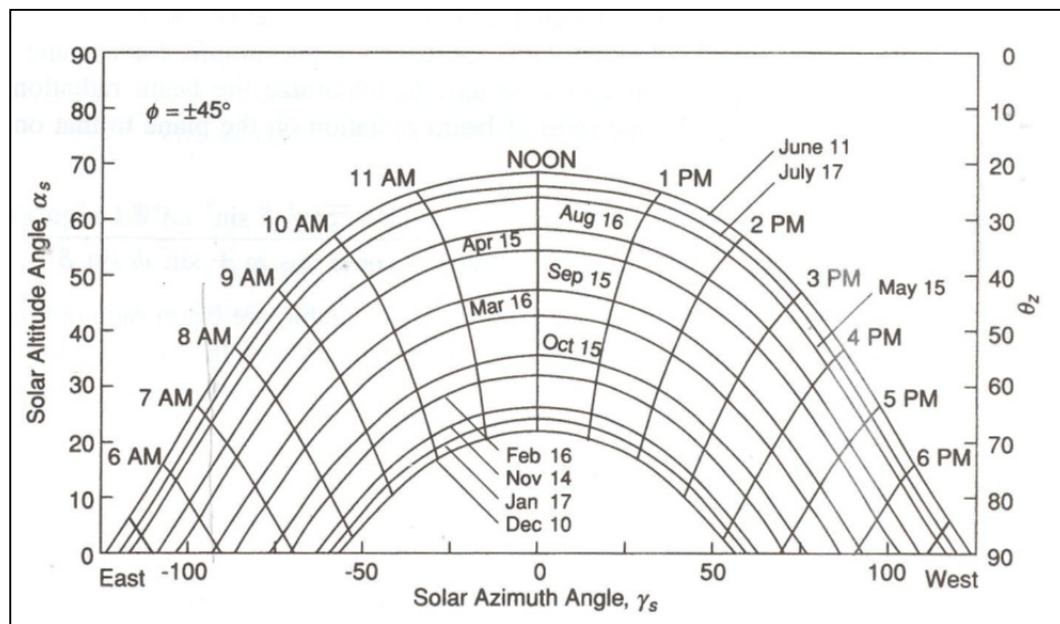


Figure 1.2 Sun's path in the sky (Duffie and Beckman, 1974)

1.3 Fundamentals of solar radiation

The radiation impinging on the earth's atmosphere is called extraterrestrial radiation. There are several conflicting reports about the accurate amount of extraterrestrial radiation. Duffie and Beckman (1974) present an equation that gives an almost accurate amount of extraterrestrial radiation as a function of the day number (n). The solar constant (I_{sc}) has been estimated as 1367 W/m^2 with an uncertainty in the order of 1%.

$$I_{on} = I_{sc} \cdot \left[1 + 0.033 \cos \left(\frac{360n}{365} \right) \right] \quad (1.1)$$

Hourly extraterrestrial solar radiation upon a horizontal (Wh/m²) surface between sunrise and sunset is given by equation 1.2:

$$I_o = \frac{12 \cdot I_{sc}}{\pi} \cdot \left[1 + 0.033 \cos \left(\frac{360n}{365} \right) \right] \cdot \left[\cos \varphi \cdot \cos \delta \cdot (\sin \omega_2 - \sin \omega_1) + \frac{\pi \cdot (\omega_2 - \omega_1)}{180} \cdot \sin \varphi \cdot \sin \delta \right] \quad (1.2)$$

where φ stands for the latitude of the location which is equal to 45°30'N for Montreal and δ is the declination angle which is found from equation 1.3:

$$\delta = 23.45 \sin \left(2\pi \cdot \left(\frac{284 + n}{365} \right) \right) \quad (1.3)$$

into which ω is the 15° per hour of angular displacement of the sun from local meridian with positive value in the afternoon and negative value in the morning. The reference meridian is used to calculate the local standard meridian. The local standard meridians are located at 15° intervals from Greenwich meridian (longitude 0°), near London. The LST for Montreal is 75°W.

Incident solar radiation on each surface consists of three components: direct radiation, diffuse radiation, and reflected radiation from the other surfaces seen by this surface. Equation 1.4 sums up the total solar irradiation on a tilted surface.

$$I_T = I_{T,b} + I_{T,d} + I_{T,refl} \quad (1.4)$$

The incident solar radiation upon a surface is a function of the tilt angle and the azimuth angle. The maximum absorption of solar radiation occurs when the panel surface is perpendicular to the sun's rays ($\theta=0$). The angle of incidence of direct radiation on a surface, θ , is given by equation 1.5 (Duffie and Beckman, 1974):

$$\begin{aligned} \cos \theta = & \sin \delta \cdot \sin \varphi \cdot \cos \beta - \sin \delta \cdot \cos \varphi \cdot \sin \beta \cdot \cos \gamma + \\ & \cos \delta \cdot \cos \varphi \cdot \cos \beta \cdot \cos \omega + \cos \delta \cdot \sin \beta \cdot \sin \gamma \cdot \sin \omega \end{aligned} \quad (1.5)$$

The angle of incidence of direct radiation for a single horizontal east-west axis tracking plane with daily adjustment is given by equation 1.6:

$$\cos \theta = \sin^2 \delta + \cos^2 \delta \cdot \cos \omega \quad (1.6)$$

The slope of the plane, β , is fixed every day and given by:

$$\beta = |\varphi - \delta| \quad (1.7)$$

The incidence angle of direct radiation for this tracking plane with continuous adjustment is given by equation 1.8, and its tilt angle is given by equation 1.9:

$$\cos \theta = \sqrt{1 - \cos^2 \delta \cdot \sin^2 \omega} \quad (1.8)$$

$$\tan \beta = \tan \theta_z \cdot |\cos \gamma_s| \quad (1.9)$$

The incidence angle of direct radiation for a single horizontal north-south axis tracking plane with continuous adjustment can be represented by the equation 1.10 and equation 1.11 represents the tilt angle of this system:

$$\cos \theta = \sqrt{\cos^2 \theta_z + \cos^2 \delta \cdot \sin^2 \omega} \quad (1.10)$$

$$\tan \beta = \tan \theta_z \cdot |\cos(\gamma - \gamma_s)| \quad (1.11)$$

For a single vertical axis tracking (azimuth tracking) plane the incidence angle of direct radiation is given by equation 1.12. The slope of the plane is fixed, therefore β is constant.

$$\cos \theta = \cos \theta_z \cdot \cos \beta + \sin \theta_z \cdot \sin \beta \quad (1.12)$$

The incidence angle of beam radiation of a tilted axis north-south tracking plane which is parallel to the earth's axis and adjusted continuously is given by equation 1.13:

$$\cos \theta = \cos \delta \quad (1.13)$$

The slope, that varies continuously, is given by equation 1.14:

$$\tan \beta = \frac{\tan \varphi}{\cos \gamma} \quad (1.14)$$

The incidence angle of direct radiation of a dual-axis solar tracking plane and its tilt angle variation are represented by the following equations:

$$\cos \theta = 1 \quad (1.15)$$

$$\beta = \theta_z \quad (1.16)$$

1.4 Radiation models

Several attempts have been done to calculating the solar radiation on surfaces. Basically, two main types of models have been presented, isotropic sky and anisotropic sky.

In isotropic sky models like Hottel's (Loutzenhiser, Manz et al., 2007), it is assumed that all diffuse radiation is uniformly distributed over the sky dome and that reflection on the ground is diffuse. Circumsolar and horizon brightening are assumed to be zero. Therefore, the total radiation on a tilted surface is assumed to be equal to the summation of the beam contribution, I_b , and the diffuse contribution on a horizontal plane, I_d . Liu and Jordan derived the isotropic diffuse model which is more precise (Noorian, Moradi et al., 2008). It assumed that radiation on a tilted surface consists in three components: direct, isotropic diffuse, and reflected from the ground. This model is easy to understand but it underestimates the amount of solar radiation incident upon tilted planes under clear and partly cloudy conditions (Duffie and Beckman, 1974).

Anisotropic sky models take into account the circumsolar diffuse and/or horizon-brightening components. Hay and Davies estimated an anisotropic sky model in which diffuse radiation from the sky is composed of an isotropic part and circumsolar part, but horizon brightening is neglected (Duffie and Beckman, 1974). This model has been utilized in this research as PVSOL Pro software is using this model to calculate the irradiance upon surfaces.

For a cloudy sky, it is valid to use the isotropic sky model to estimate the hourly solar radiation on a tilted surface (I_T). The isotropic sky model assumes that the intensity of diffuse radiation is uniform over the whole sky. Therefore, the incident diffuse solar radiation on a tilted surface depends on the fraction of sky seen by it. To calculate the incident reflected radiation from the ground, the field of view seen by the surface is considered as a diffuse reflector (Loutzenhiser, Manz et al., 2007).

$$I_T = I_b \cdot R_b + I_d \cdot R_d + I \cdot R_{refl} \quad (1.17)$$

I_b is hourly direct solar radiation on a horizontal surface (Wh/m^2). Geometric factor (R_b) is the ratio of direct solar radiation on an inclined surface to the direct solar radiation on a horizontal surface.

$$R_b = \frac{\cos \theta}{\cos \theta_z} = \frac{\cos(\varphi - \beta) \cdot \cos \delta \cdot \cos \omega + \sin(\varphi - \beta) \cdot \sin \delta}{\cos \varphi \cdot \cos \delta \cdot \cos \omega + \sin \varphi \cdot \sin \delta} \quad (1.18)$$

The angle factor (R_d) for an inclined surface to the sky at any time is presented by

$$R_d = \frac{1 + \cos \beta}{2} \quad (1.19)$$

The angle factor for an inclined surface towards the ground (R_{refl}) depends on ground reflection coefficient (ρ_g):

$$R_{\text{refl}} = \rho_g \cdot \left(\frac{1 - \cos \beta}{2} \right) \quad (1.20)$$

The anisotropic sky model divides the sky into two zones, a zone for part of the sky around the sun (circumsolar area) and one for the remaining portion of the sky. The diffuse solar radiation from the circumsolar area is projected onto the inclined surface in the same manner as for direct solar radiation. Therefore, R_d is

$$R_d = \left[(1 - A_i) \cdot \left(\frac{1 + \cos \beta}{2} \right) + A_i \cdot R_b \right] \quad (1.21)$$

To compare the circumsolar and isotropic radiation, the anisotropic index (A_i) is defined:

$$A_i = \frac{I_b}{I_o} \quad (1.22)$$

1.5 PV softwares

PV softwares are used to simulate PV systems and estimate their efficiency, power output, irradiance, etc. Most of the programs use meteorological databases and radiation models to

calculate the solar irradiance on PV modules. This section briefly presents various PV softwares and discusses their preponderant features. The interested reader should consult the reference provided at the end of the short reviews for details.

1.5.1 PVDesignPro

PVDesignPro is a software developed by Maui Solar Energy Software Corporation (MSESC) and Sandia National Laboratories. This software uses an hourly time-step in system performance simulations. It uses two models to estimate solar radiation: Hay-Davies-Klucher-Reindl (HDKR) and Perez et al. PVDesignPro uses TMY2, TMY3, and METEONORM data as meteorological databases. This software also has a financial analyzer that determines cash flow, payback period, etc.

1.5.2 Solar advisor model

This software (SAM) was developed in 2006 by a partnership with the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL). This software was created for stand-alone systems and it is able to assist the financial analyses. It uses Liu and Jordan (1963), Hay and Davies (1980), Reindl (1988) and Perez et al. (1987, 1988) radiation models. SAM uses TRNSYS code to implement the array performance models. This software uses TMY2, TMY3, EnergyPlus Weather (EPW), and METEONORM data as weather data base.

1.5.3 PVSYST

PVSYST was created by Energy Group at the University of Geneva in Switzerland. This software provides the ability for user to modify numerous parameters. It uses Hay & Davies and Perez et al. models for solar radiation modeling. PVSYST has the ability to use many datasets for weather conditions including METEONORM, Satellites, TMY2/3, ISM-EMPA, Helioclim-1 and -3, NASA-SSE, WRDC, PVGIS and RETScreen. PVSYST has also a

financial analyzer. One more interesting feature of PVSYST is a 3-D shading tool. This feature provides the ability for user to draw a PV system and see potential shading impacts.

1.5.4 PV F-Chart

PVF-Chart was developed at the University of Wisconsin Solar Energy Laboratory. It uses isotropic sky model (Liu and Jordan) model for irradiance upon modules. For weather data, it uses TMY2 data. It has also the ability to provide an economic analysis for PV systems.

1.5.5 RETScreen

RETScreen is a program created by Natural Resources Canada to analyze financial and environmental aspects of various renewable energy technologies. It uses an isotropic sky model (Liu and Jordan). For weather data, it uses TMY2 and NASA-SSE (www.retscreen.net).

1.5.6 Polysun

Polysun was developed by Vela Solaris Company in Switzerland. There is no available detail about what types of irradiance or array performance models are used in this software. For weather data, it uses Meteotest data. It also has an economical analyzer.

1.5.7 SolarPro

SolarPro is a software from Laplace System based in Kyoto, Japan. It has the ability to analyze different orientations of PV systems and it has also a 3-D shading tool. There is no detail about what radiation model and weather data are used in this software. It has also an economical analyzer.

1.5.8 PVSOL

PVSOL was developed by Valentin Energy Software in Germany and its first version was released in 1998. PVSOL uses an anisotropic sky model (Hay and Davies). The performance of the system is computed by incoming irradiance, module voltage at Standard Test Conditions (STC), and an efficiency characteristic curve. PVSOL has the ability to use either a linear or dynamic temperature model. For weather data, it uses METEOSYN, METEONORM, PVGIS, NASA-SSE, SWERA, and user inputs. In this study the version of PVSOL called PVSOL Pro 4.5 has been utilized. The special feature of PVSOL is having the ability to change the tilt and azimuth angles and having a variable amount for them. Therefore, it has the ability to model the solar tracking PV systems. Furthermore, PVSOL Pro provides the ability for users to change all specifications in database and make their own PV systems. This software has also an economical analyzer toolbox.

The interested reader may consult (Klise, 2009) for more details.

1.6 Solar tracker

Solar tracker is a device that keeps the PV modules or thermal collectors perpendicular to the sun's rays during the day. Solar trackers are also used for orienting lenses, reflectors or other optical devices toward the sun. The required tracking accuracy depends on the application. Solar concentrators require high accuracy of tracking; they are not able to operate without tracking. On the other hand, flat plate collectors require less accuracy.

There are two types of solar trackers based on the rotation axes: single axis and dual-axis. Single axis trackers have one degree of freedom as an axis of rotation. Three orientations of single axis solar trackers are common: horizontal, vertical, and tilted.

1.6.1 Horizontal axis

This type of single axis trackers has a horizontal axis of rotation with respect to the ground. Figure 1.3 shows a schematic of a horizontal single axis tracker. These trackers are effective in low latitude locations where the sun passes overhead in the sky. This axis could be oriented in east-west or north-south directions, depending on the selected strategy for tracking.

1.6.2 Vertical axis

This type of single axis trackers has a vertical axis of rotation and they are effective in high latitude locations. Vertical axis trackers track the sun from East to West over the course of the day. PV panels are installed on vertical axis with a tilt angle, Figure 1.4 schematically shows a vertical single axis tracker which are also called by azimuth trackers.

1.6.3 Tilted axis

Tilted axis trackers have an inclined axis of rotation. Figure 1.5 schematically depicts a tilted axis tracker. If the tilt angle of axis is equal to the latitude of installation location it would be called polar tracker.

1.6.4 Dual-axis

Dual axis trackers have two degrees of freedom as rotation axes; they have both horizontal and vertical axes to track the sun more precisely. Figure 1.6 schematically illustrate a dual axis tracker.

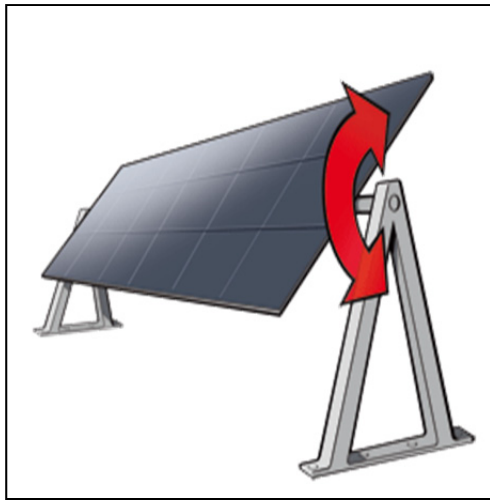


Figure 1.3 Horizontal axis tracker
(Linak, 2012)



Figure 1.4 Vertical axis tracker
(Linak, 2012)

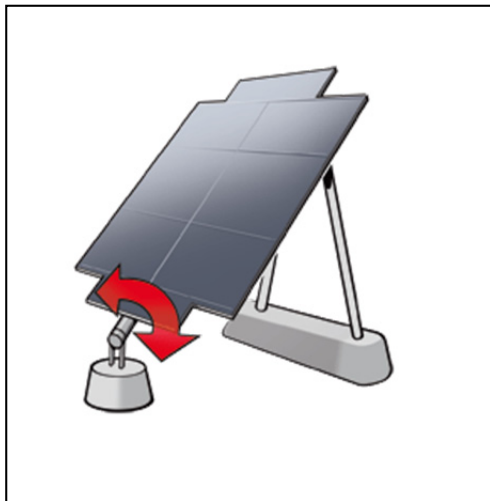


Figure 1.5 Tilted axis tracker
(Linak, 2012)

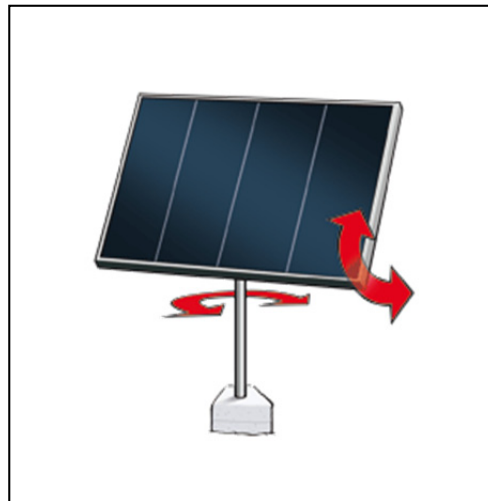


Figure 1.6 Dual-axis tracker
(Linak, 2012)

CHAPTER 2

LITERATURE REVIEW

In recent years, there has been an increasing amount of literature on PV systems. Numerous attempts have been made to improve the performance of such systems. Several studies have focused on solar tracking as a method for performance improvement. In this chapter, a body of literature since last decade is reviewed. This chapter has been divided into four parts. The first part deals with effect of tracking the sun on the performance of PV systems. The second part describes the economic effects of using solar trackers. The third part explains some case of studies about using solar trackers. Finally, an organization chart of solar tracking is presented as a conclusion.

2.1 Performance evaluation

This section attempts to show the role of solar trackers in improving the PV systems performance and producing more electricity. There are two basic methods to evaluate this effect; some authors have used experiments while others have estimated it theoretically.

2.1.1 Experimental studies

Huang et al. (2007) designed and tested a single axis three position tracking mechanism. This tracking method adjusts the PV module only at three angles: morning, noon and afternoon. The analytical part of this study shows the optimal stopping angle in the morning and afternoon. The optimal stopping angle is 50° from the solar noon position. Another important angle is switching angle that adjusts the best time to change the orientation of the PV panels. The results show the optimal switching angle of 25° . The stopping and switching angles are independent of latitude. The proposed tracking mechanism increases power generation of 24.5% as compared to a fixed system tilted at latitude angle in the areas with latitudes of less than 50° . The main advantages of this mechanism are simple structure and low cost.

Huang et al. (2011) tested this tracking system for a period of 13 months. The measurements of particular days show 35.6% more generated electricity for this tracking system compared to fixed PV system in a partly cloudy weather with daily total solar radiation of 11.7 MJ/m^2 , and 35.8% in clear weather with daily total solar radiation of 18.5 MJ/m^2 . These results indicate that this tracking mechanism can produce electricity in amounts very close to dual axis continuous tracking, and that the generated electricity would be increased by any increase of daily total solar radiation. The monthly increase of generated electricity by the tracking PV system is between 18.5% and 28%. In Taiwan, with low amount of radiation, this tracking system can produce electricity in amounts very close to the single axis continuous tracking.

Abdallah et al. (2004) designed and constructed an open loop dual-axis solar tracking controlled by a PLC (programmable logic controller). The total solar radiation was measured by two pyranometers that were installed on tracked and fixed modules. The results from comparing a system tilted at 32° and a tracking system show 41.34% more total daily solar radiation for a tracking system. Furthermore, the consumption of electrical motor and control system is less than 3% of the power increase by the tracking system.

Salah Abdallah (2004) investigated the effect of using four different types of solar tracking systems on power generation of PV systems located in Amman, Jordan. He designed, constructed and studied four open loop systems including dual-axis, vertical axis, single axis east-west and single axis north-south tracking that are controlled by PLC. The I-V characteristics of the systems were measured during a day to find the power generation. The increase of power generation by each system is greater than of a tilted system at 32° by 43.87%, 37.53%, 34.43%, and 15.69% for the dual-axis, east-west, vertical, and north-south tracking system, respectively.

Helwa et al. (2000) also compared four configurations of PV systems including a south facing fixed system tilted at 40° , an single-axis tracking system, a tracker with 6° tilted axis (north-south tracker), and dual-axis tracking system. All systems were controlled by

microprocessors. The comparison is based on one year period of measurement of solar radiation on systems and their power output. The controllers of azimuth and north-south tracker used time, date, and site parameters to calculate the sun's position. The dual-axis tracker's controller used digital signals from a PC that computes the sun's position by a software. The comparison's results show annual increase of collected radiation by azimuth, north-south and dual-axis trackers of 18%, 11%, and 30%, respectively, over the fixed system. Analyses of tracking consumption show a proportional relation between tracking accuracy and consumption. The consumption of north-south tracker is 50 Wh/day and 22 Wh/day with the tracking errors of $\pm 0.56^\circ$ and $\pm 10^\circ$, respectively.

Teolan (2008) proposed a two-positional tracking method that rotates the flat plate collector twice a day with predefined symmetrical and asymmetrical deflections. The effect of different tilt and azimuth angles of the deflected surface on daily and seasonal gain were studied. Evaluation of simulations and experiments shows 10% to 20% more seasonal energy yield for the proposed tracking method than for a fixed system tilted at optimal angle.

Koussa et al. (2011) investigated the effect of using different types of solar tracking on PV systems performance and power output. Five solar tracking and two fixed systems were studied and tested including fixed tilted at seasonal optimum angle, fixed tilted at yearly optimum angle, vertical axis tracking (east-west tracking), inclined axis tracking tilted at seasonal optimum angle, inclined axis tracking tilted at yearly optimum angle, and two dual-axis tracking systems. Direct, diffuse and reflected solar irradiances collected by systems are calculated by using main parameters including solar beam incidence angle, instantaneous slope of the panel, and panel azimuth. The hourly direct normal radiation, horizontal global radiation, diffuse radiation, and temperature were measured in different seasons of the year including six clear days, seven partially clear days with different clearness indexes, and five cloudy days (18 days of measurements). The electricity production of each system was evaluated. The results show that during clear days, tracking the sun is very useful, that during cloudy days it is unnecessary, and that during partially clear days, based on clearness index, it could be unnecessary or useful. The largest difference of electricity production between

tracked and fixed systems was observed during the morning and afternoon. During cloudy days, the optimal position is horizontal. The electricity production depends on three main parameters: sun tracker consumption, sky state, and day length. Dual-axis tracking PV system produces the highest amount of electricity among these systems, and decrease gradually from single inclined to vertical axis and from seasonal optimum angle to yearly optimum angle.

Kelly et al. (2011) analyzed four PV systems tilted at different angles for a period of eight months to determine the optimal tracking algorithm. Measurements were done in different seasons with various temperatures and various amounts of radiation. One system was tilted at latitude angle, one system at 15° more than latitude, one system at 15° less than latitude, and the last one was fixed horizontally. The solar irradiance was measured by silicon-photodiode pyranometers sensors installed on each system. One system always looked directly toward the sun (DTS) during the noon, which maximized the capture of direct radiation. Another system is always in horizontal position (H), which maximized the capture of diffuse radiation. In order to find the optimal angle to capture more solar energy in both clear and cloudy days the ratio of H/DTS has been studied. Consequently, in sunny days, H/DTS ratio is 0.5; it means that tracking the sun would allow to absorb twice as much solar energy as a horizontal system. In cloudy days the H/DTS ratio becomes 1.37; it means that over a whole cloudy day a horizontal system would receive 50% more solar energy than a dual-axis solar tracking system. However, over a whole year, the hybrid system (both tracking and horizontal) would yield 1% more than a tracking system. As a result, the optimal solar system is a dual-axis solar tracking system to receive the maximum amount of direct radiation and turn the module toward the zenith in cloudy days.

Kelly et al. (2009) studied a PV system with a tracker to find the optimum position in cloudy conditions. Dual-axis solar tracking improves the capture of solar irradiance by 30-50% compared to a fixed system. In sunny days, the overall radiation consisted of 90% of direct radiation and 10% of diffuse radiation. In cloudy days, 100% of the radiation is diffused. The results showed that in overcast conditions, horizontal systems capture 50% more solar

irradiance than a system that tracks the sun every day regardless of the sky condition. The Isotropic Diffuse Model agrees with the experimental results of this study in overcast conditions. This study proposed that a tracking system should use simple algorithms and sensors to determine the overcast conditions and move to the horizontal position in cloudy conditions.

Mousazadeh et al. (2011) designed, constructed and evaluated a solar tracking system installed on a mobile structure. The solar system designed and installed on a hybrid electric tractor to provide energy for tractor. The tracker strategy is independent of date and time. Four light dependent resistive (LDR) sensors have been installed on the system to sense the beam irradiance and each pair of LDR have been separated by a shading device. The PV system consisted of 12 panels of 6 m² area and it produced 540 W of electricity. A microcontroller controlled the tracking. As a result of experiments in April, this tracking system collected up to 30% more energy than a horizontal system. The tracker consumption is almost 1.8% of the energy difference (30%).

Oner et al. (2009) designed and constructed a spherical motor controlled by a micro controller for a solar tracking system. Spherical motors are able to move in three independent dimensions linearly and circularly. This motor consists of a rotor with a four-pole spherical magnet, and eight stator poles. Furthermore, two photo transistors have been used for sensing the solar irradiance. The output voltage was measured for a day in order to compare the tracking system with fixed systems. Results analysis shows a considerable performance improvement especially in the afternoon.

Abu-Khader et al. (2008) compared and evaluated different types of tracking. Four systems have been constructed and studied including fixed, vertical axis tracking, north-south tracking, and east-west tracking. The systems are controlled by an open loop PLC controller. Pyranometers, installed on panels, measure the solar irradiance. Two drivers provide the tracking motion, the first for joint rotating about the vertical axis, the second for north-south

or east-west tracking. Experiments show that the north-south tracking is the optimum one and that it produces 30-45% more output power than the fixed system tilted at 32°.

Al-Mohamad (2004) designed and constructed a single-axis solar tracking system controlled by a PLC unit. Two photo resistors installed on the modules are separated by a barrier to provide shadow for one of them. SUCOSOFT has been utilized to develop a proper program to control, monitor and collect data. A program was developed with Visual Basic 5 for PC monitoring through the RS232 serial port and automatic detection. It is found that in the morning and evening the tracking system produces 40% more output power than a fixed one, and that the daily output power improvement is at least 20%. Using a PLC unit as a controller allows to connecting many PV panels in series and parallel. It permits cost reduction of tracking systems.

Michaelides et al. (1999) investigated the effect of using solar tracking systems in solar water heater systems in Cyprus and Greece. The authors compared three different systems: fixed, azimuth tracking, and seasonal tracking (the collector slope changed twice per year). Their simulations were carried out by TRNSYS. The results of yearly solar fraction in Nicosia (Cyprus) show 87.6% for azimuth tracking, 81.6% for seasonal tracking and 79.7% for the fixed system. In Athens (Greece) results show 81.4%, 76.2% and 74.4%, for azimuth tracking, seasonal tracking and fixed systems, respectively. The azimuth tracking system has the best performance in both locations.

Abdallah et al. (2008) improved a solar still with a single axis solar tracking system. A comparison between fixed solar still and tracked system shows 22% more productivity by using a tracking system over a clear day. It also improves the overall efficiency for 2%. A PLC unit was utilized to control the solar tracker. The power consumption of the tracker is less than 3% of the increased energy by tracker over a day.

Kelly et al. (2009) measured the solar irradiance of PV systems during overcast periods. They utilized six sensors to measure the irradiance upon a horizontal (H) and a dual-axis

tracking which looks directly toward the sun (DTS). The following equation was derived to calculate the tracking advantage (TA) of a dual-axis tracking system over a horizontal system.

$$TA = \frac{\left(1 - \frac{H}{DTS}\right)}{\left(\frac{H}{DTS}\right)} \quad (2.10)$$

Since all measurements were performed for completely cloudy days, they obtained a negative value of TA ranging from -0.17 to -0.45 with an average of -0.31. These results led to conclude that in cloudy conditions, especially for completely overcast days, we capture more solar energy by orienting the solar modules towards the zenith (horizontal position) as compared to the system that simply follows the sun's path (Kelly and Gibson, 2009).

2.1.2 Theoretical estimations

Li et al. (2011) suggested a mathematical procedure for estimating the annual collectible radiation on fixed, vertical axis tracking, and dual-axis tracking PV systems based on the monthly horizontal radiation. The results show that, annual incident radiation upon a PV module depends on local solar resource and tracking methods. For azimuth tracking the yearly optimum angle depends on the local latitude and weather condition. The maximum annual collectible radiation on azimuth solar tracking systems is 96% of that on dual-axis solar tracking systems. For azimuth tracking system the annual collectible radiation is 28% more than fixed systems in areas with high amount of radiation, and this amount becomes 16% in areas with low amount of radiation.

Lubitz (2011) implemented a model to investigate the effect of manual tilt adjustments in fixed and tracking PV systems. Hourly Typical Meteorological Year (TMY3) and Perez radiation model were utilized to simulate the incident solar radiation on PV systems in 217 locations of the United States. The optimum tilt angle for a fixed system is equal to the

latitude at low latitude areas to up to 14° less than latitude in high latitude areas. Results show that azimuth tracking increases the annual incident solar radiation of 29% as compared to a fixed system tilted at optimum angle, and that dual-axis tracking increases that of 34%. Manual tilt angle adjustments increase the annual irradiance on fixed systems of 5%, and on azimuth tracking systems of 1%.

Lave et al. (2011) calculated optimum tilt and azimuth angles in continental United States. They employed the Page model to 10 km gridded data. While rules of thumb propose that maximum global irradiance (GI) is collectable at latitude tilt angle and 0° azimuth, they found that for most locations in continental United States higher GI could be obtained by deviating from this rule. The data derived from the satellite have been used in this study for GHI and DHI. They used Page model to find global hourly irradiance (GI) for a panel with any tilt and azimuth angles. They considered the direct, diffuse, and reflected irradiance. Page model was employed to find the diffuse irradiance. The reflected radiation which is function of panel tilt angle, albedo, and global horizontal radiation is modeled. To determine the optimum tilt and azimuth angles the Page model was written in function form with inputs of panel tilt, panel azimuth, latitude, longitude, time, G_h , and D_h . Their results present that, the optimum tilt angle could be up to 10% less than the latitude tilt. However, the tracking systems produce more electricity than fixed. In areas with large amount of solar radiation, solar tracking is very effective. In areas with high amount of solar radiation, tracking systems are suggested since the increased power is adequate to recover the higher initial costs, maintenance costs, and energy consumption of the tracker. Their analysis didn't consider the ambient temperature effect on PV efficiency since the temperature effect is small and depends on PV temperature coefficients.

Bin Ai et al. (2003) derived a mathematical formula for estimating the hourly and daily irradiance on azimuth three step tracking and hour angle three step tracking systems. The hourly and monthly irradiance on PV panels was calculated. The results show that azimuth three step tracking, hour angle three step tracking, and dual-axis azimuth three step tracking receives 66.5%, 63.3% and 72% more radiation, respectively, as compared to horizontal PV

system. For calculating the diffuse radiation, the isotropic model of sky diffusion was employed, this model is not as precise as anisotropic models like Hay or Perez, but it is simpler.

Chang (2009) used an empirical model to calculate the irradiance upon single axis tracking PV module, and compare with a fixed system. The results show up to 33.9% more recovery for a single axis tracking system in four specified days of a year and 27.6% more energy recovery over a year as compared to fixed system. For the areas with latitude of less than 65°, the optimal tilt angle is 0.8 of latitude. The irradiance ratio of single axis tracking and fixed module is 1.3, but cloudy conditions and air pollution reduce this rate. The observed irradiance is much less than the predicted one by empirical model, the yearly gain for tracked panels is 14.3% more than for fixed panels.

Chang (2009) calculated the electricity production of a single axis tracking PV system in different azimuths and tilt angles in Taiwan. This study has considered both extraterrestrial and global radiation. The annual gain shows 51.4%, 28.5%, and 18.7% from extraterrestrial, predicted and observed radiation, respectively, for the single axis tracker with yearly optimal tilt angle. These gains for the single axis tracker system with monthly optimal tilt angle are 45.3%, 25.9% and 17.5%, respectively. The yearly conversion efficiency of a fixed module is 10.2%, 9.2%, and 8.3% for the extraterrestrial, predicted and observed radiation, respectively. While the clearness index is decreased, the optimal tilt angle becomes flatter. The yearly output energy when the panel is faced to the west or east is less 11%, 10%, and 5% for extraterrestrial, predicted and observed radiation, respectively, as compared to the south facing system.

Chang (2009) also calculated the performance of an east-west oriented single axis tracker. This research has also considered three different sources of radiation: extraterrestrial, global predicted by empirical model under clear sky condition, and global radiation observed in Taiwan. It was found that the yearly gains increase with the radiation level. The results show an increase of 21.2%, 13.5%, and 7.4% for the extraterrestrial, predicted, and observed

radiation, respectively. These increases are considerably less than those obtained for north-south single axis tracker. By increasing the tilt angle the irradiance would be increased too, but not in overcast conditions. Therefore, the 45° is proposed for safety considerations about energy collection through the entire year.

2.2 Economical investigation

In 2006, Huang et al. (2007) designed a single axis three position tracking with low concentration ratio reflector. The three positions of tracking are morning, noon and afternoon. This tracking strategy caused an increase of 24.5% of power generation over that of fixed module. Utilization of low ratio (2X) concentrator caused 23% more power generation and total increase of power generation is 56% more than for a horizontal system. It is estimated that the additional cost for tracking mechanism, reflector and PV packaging is 100 US dollars for a 100 W PV module. The additional cost would be higher for larger modules due to the increase in weight structure and PV area. A relation in US dollars between the additional cost and power was derived:

$$C_a = 100 + 0.5(P_v - 100) \quad (2.1)$$

The additional power generation retrieves this additional cost. Figure 2.1 shows the price reduction of this system:

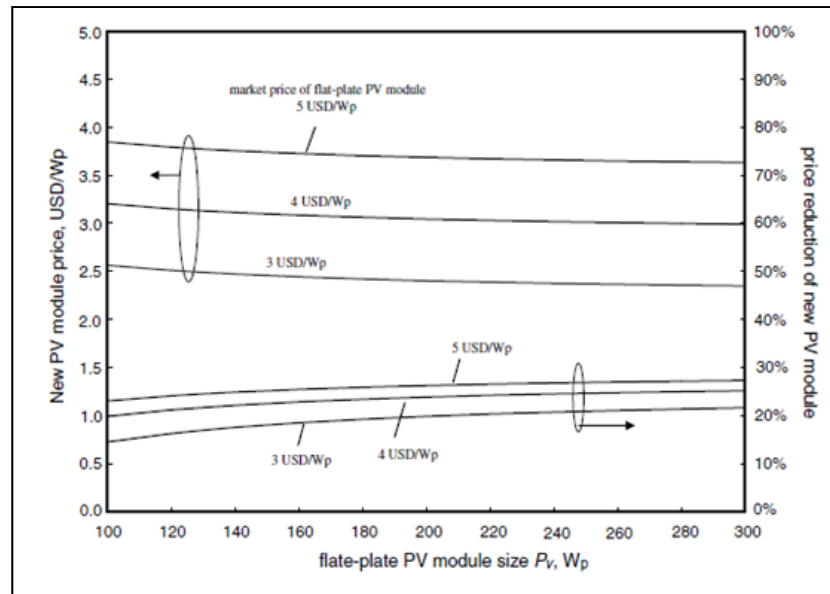


Figure 2.1 Price reduction estimation for PV module with one axis three positions tracking with 2X concentrator reflector (Huang and Sun, 2007)

This figure shows that the price reduction is always between 20% and 30% for various market prices of PV modules. The price reduction does not change too much when the size of the module is above 160 W. For smaller PV module size (<100 W) the price reduction is not significant if the market price of PV module is less than 3 USD/W (Huang and Sun, 2007).

According to the long-term tests, it was concluded that, the cost of a one axis three-positions tracking system is much cheaper than the conventional tracking system; it is very simple in design and easy mounted on the wall. The overall cost of the tracking system (structure, motor, controller, driving mechanism) is around 100 USD in mass production in 2011, it is almost the same as the regular mounting cost of a rooftop PV system. Hence, in Taipei, this tracking PV system produces 23.6% more electricity compared to rooftop PV systems, while no extra cost is necessary. Therefore this tracking system is appropriate for building integrated applications and for ground mounting systems if the PV module carried by tracker has power of more than 600 W (Huang, Ding et al., 2011).

Michaelides et al. (1999) made a comparison between cost effectiveness of solar water heaters for different tracking modes in Cyprus and Greece. They compared a fixed, vertical single axis tracking, azimuth tracking, and seasonal tracking (collector slope changed twice per year) thermo syphon solar water heaters. The simulations were carried out with TRNSYS. The analyses show that the most cost effective system is the traditional fixed system. Although the tracking systems can receive more solar radiation, their initial cost is too high. TRNSYS subroutine economic analysis has been used to carry out the economic evaluation. The fixed system is the most effective system due to less initial cost and provides a payback time of 5 years as compared to 6 years with seasonal tracking and 10 years with single axis tracking, and the tracking systems need maintenance twice per year but the fixed one does not.

2.3 Case of studies

Solar tracking systems are used for many applications. In this study, Khalifa and Al-Mutawalli (1998) investigated the effect of using a dual-axis solar tracking system for a compound parabolic concentrator (CPC) and he got 75% more collected energy than with a fixed CPC. The tracking system used in this study consisting of two sub systems and each one consists of two adjacent phototransistors. A gearbox and a DC motor provided tracking motions. The tracking system tracks the sun every three or four minutes in the horizontal plane and every four or five minutes in the vertical plane. The power consumption of the tracker is about 0.5 Wh per day. The performance increase depends on the flow rate through the collector; the best performance was achieved in 25-45 kg/hr. Finally, the authors proposed the tracking systems with CPC collectors when the performance improvement offsets the extra cost of tracker.

Solar trackers are used also in solar dryers. Mwithiga and Kigo (2006) designed and tested a solar dryer with a simple solar tracking system that tracks the sun manually. The angle of the dryer is changed three, five or nine times per a day and each time of 15°. This system reduced the coffee moisture from 54.8% to 13% during two days as compared to 5-7 days for

a non-tracked dryer. Against their first guess, tracking the sun didn't cause a significant decrease in the length of the drying duration.

2.4 Organization chart

Taking into consideration of all reviewed articles, there are two main types of sun trackers according to their drive types: active and passive. Active trackers are controlled and driven by a closed loop or open loop control strategy. Active trackers use motors and gears to follow the sun, while passive trackers use a low boiling point compressed gas fluid. Solar heat creates gas pressure and imbalance that cause the passive tracker to move. The passive trackers are not as precise as active trackers. Sun trackers are classified as single axis and dual-axis solar trackers. A single axis tracker could have a horizontal, vertical, or tilted axis of rotation. A horizontal axis tracker tracks the sun from East to West or from North to South; it depends on the geographical situation where the PV system is located. If the rotation axis of a tilted axis tracker tilted at latitude angle and track the sun from East to West it is called by Polar tracker.

2.5 Summary

According to the literature, the dual-axis tracking systems receive more solar radiation and produce more electricity than the other systems. Dual-axis tracking systems produce between 20% and 50% (depends on location and weather condition) more power than fixed systems tilted at latitude angle. Single-axis tracking systems provide 15% to 45% (depends on type of tracking, location, and weather condition) more power than the tilted systems. Azimuth tracking systems can capture 96% of the annual solar radiation captured by a dual-axis tracking system. Moreover, two-positions and three-positions tracking strategies can produce 10% to 25% more output power than a fixed system tilted at latitude angle. It is worth noting that single-axis two-position and three-position trackers are significantly simpler and cheaper than the continuous dual-axis trackers.

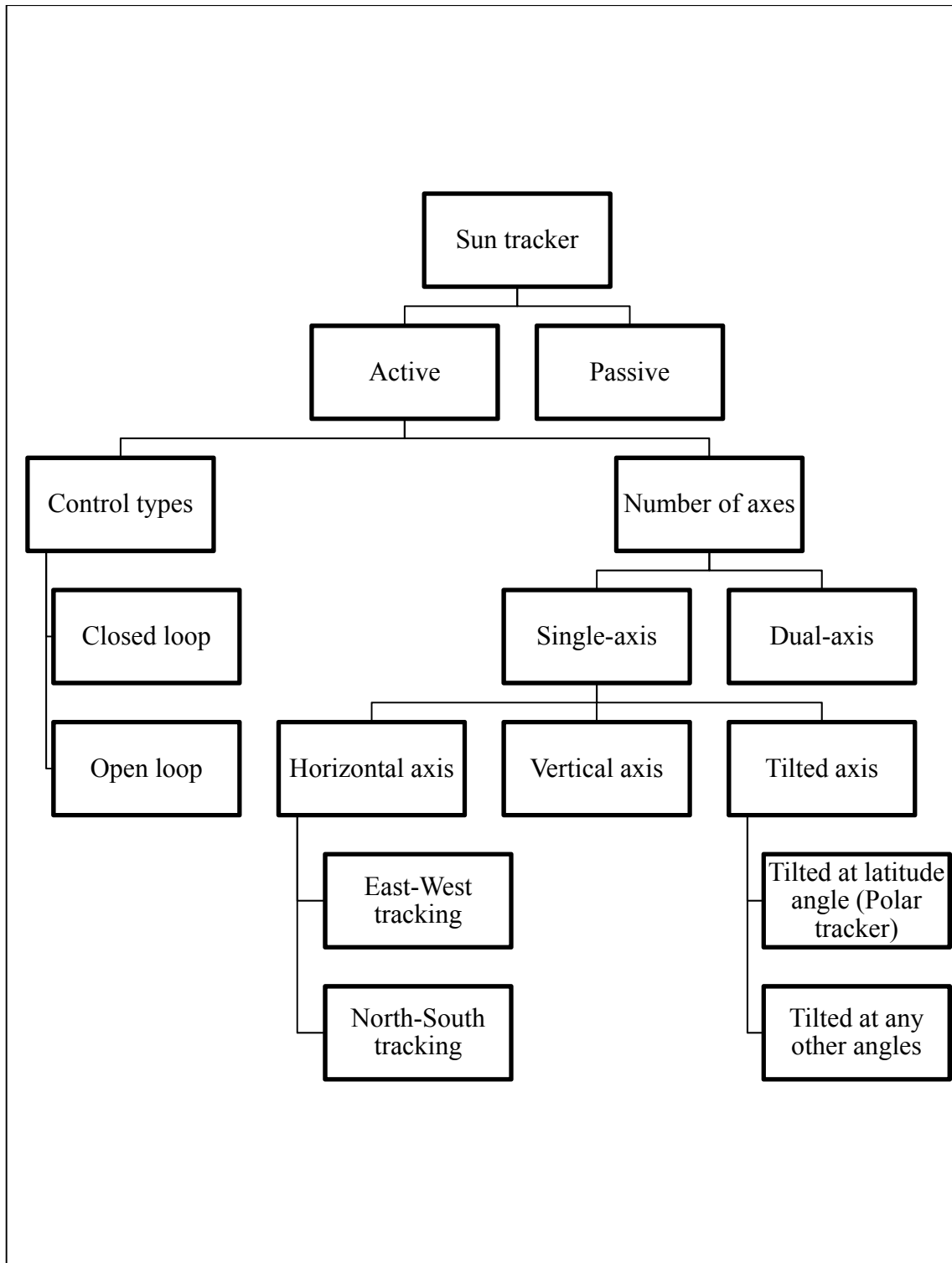


Figure 2.2 Sun trackers classification chart

CHAPTER 3

SIMULATIONS AND RESULTS

This chapter investigates the performance of different configurations of PV systems. To this end, four locations with different weather and environmental conditions have been selected: Montreal (Canada), Casablanca (Morocco), Ouagadougou (Burkina Faso), and Olympia (U.S.A). These locations are boldly classified as cold, mild, hot, and cloudy areas. To systematically investigate the effects of each environment, ambient temperature and albedo, on the performance of PV systems, numerous analyses have been done. Under weather conditions of each location, four configurations for the PV systems are studied hereafter named: horizontal, inclined, single-axis tracking, and dual-axis tracking. This chapter first gives a brief explanation of the systems and their components characteristics. Then it discusses each case in details. The simulations have been carried out with PVSOL Pro for daily and monthly periods. The hourly meteorological database (average of 20 years) called MeteoSyn has been employed in all simulations. Arrays irradiance and electricity production for each system has been analyzed. Furthermore, the tracking advantages versus the horizontal and tilted systems were computed for daily and monthly periods. The performance analysis of the systems focuses on array irradiance, electricity generation and efficiency. Systems efficiency is an essential parameter in demonstration of systems performance. Efficiency presents the amount of losses experienced and how well the system converts solar radiation to the electricity. Inefficiencies are attributed to: module mismatch, diodes, wiring and connections, snow cover, air pollution, high operating temperature, and conversion of electricity from DC to AC. This work doesn't consider the air pollution and trackers consumption. An anisotropic sky model (Hay and Davies, 1980) has been employed to estimate the hourly incident solar irradiance on PV systems. The performance of a PV system is computed by incoming irradiance, module voltage at Standard Test Conditions (STC), and the efficiency characteristic curve.

3.1 Systems description

Similar PV arrays have been used for all locations. Each array consists of 48 Si Polycrystalline PV modules. They are connected to each other in four series outline and each series consists of 12 modules. The system has four inverters that convert the DC current from the arrays to AC current compatible with electrical appliances. Figure 3.1 shows a simple schematic of the systems configuration. Each system has a total installed capacity of 14.40 kW and total PV area of 92.1 m². The technical specifications of PV modules and inverters are shown in Table 3.1 and Table 3.2. The efficiency of PV panels under standard test conditions (STC) is 15.6%. The module's temperature coefficient of power is -0.45%/K.

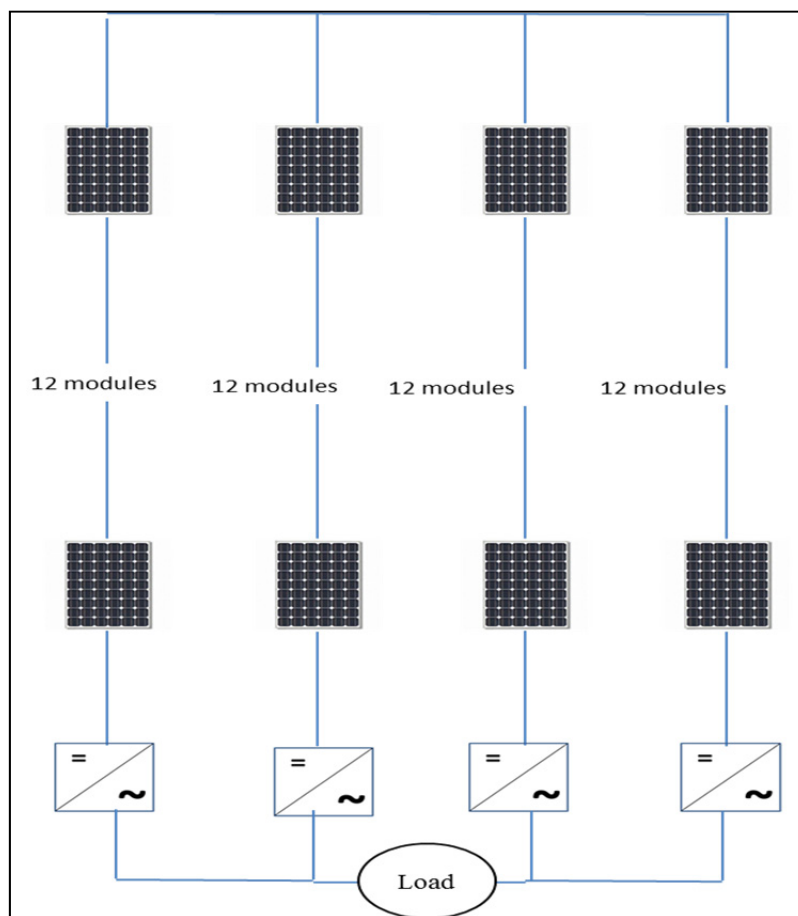


Figure 3.1 Systems configuration

Table 3.1 Electrical and mechanical characteristics of PV modules

Specification	value
Output power	300 W
Efficiency (STC)	15.6%
Height * Width	1.954 m × 0.982 m
Weight	27 kg
Temperature coefficient of voltage	-157.5 mV/K
Temperature coefficient of current	5.2 mA/K
Temperature coefficient of power	-0.450%/K
Open-circuit voltage	45 V
Short –circuit current	8.74 A

Table 3.2 Electrical characteristics of inverters

Specification	Value
Maximum DC power	5.30 kW
Maximum AC power	4.80 kW
Stand-by consumption	11 W
Night consumption	0 W
Maximum input voltage	800 V
Maximum input current	14.5 A
Peak efficiency	96.4%

Four orientations of PV systems have been studied in this thesis:

- System A: horizontal
- System B: inclined (tilted)
- System C: single-axis tracking
- System D: dual-axis tracking

System A is a simple array fixed in horizontal position. System B is tilted at yearly optimum angle computed by PVSOL. System C is a single-axis tracking (vertical axis) PV array and the panels have been tilted on the axis at yearly optimum angle. System D is a dual-axis tracking PV system that tracks the sun with two axes.

3.2 Case I: Montréal

Montreal is located at latitude of $45^{\circ} 30' \text{ N}$ and longitude of $73^{\circ} 35' \text{ W}$. Montreal's climate is classified as humid continental with large temperature fluctuations during a year. The average high temperature in hot and humid summers is 26°C and the average low temperature is 16°C . In cold, snowy and windy winter the average high temperature is -5°C and the average low temperature is -13°C (Canadian Climate Normals, 2000).

System B is faced to the south (azimuth angle of 0°) tilted at yearly optimum angle. Figure 3.2 shows the yearly mean daily radiation for South-facing systems with various tilts in Montreal. As it can be seen from the Figure 3.2 the radiation varies slowly around the 40° tilt angle. Therefore, 40° was considered as the yearly optimum tilt angle for the system B.

System C is a single-axis tracking PV array and the panels are installed on the axis with a tilt angle of 55° . Figure 3.3 shows yearly mean daily radiation for azimuth tracking systems with various tilt angles in Montreal. As it can be seen from this figure the radiation varies slowly around the 50° tilt angle.

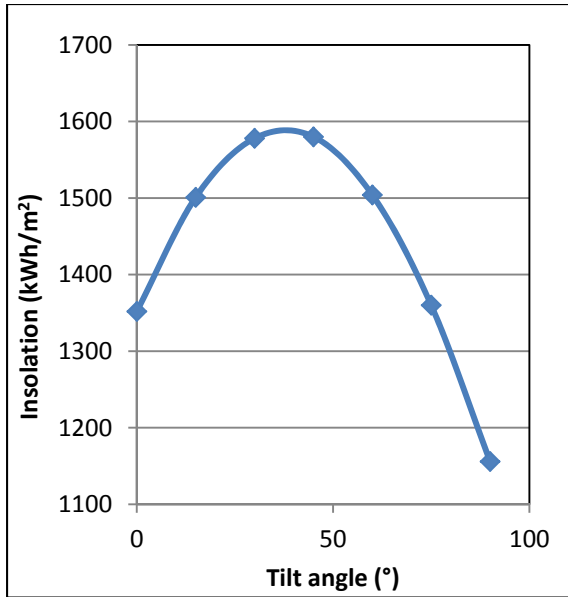


Figure 3.2 Yearly mean daily irradiation of a module tilted at various angles in Montreal

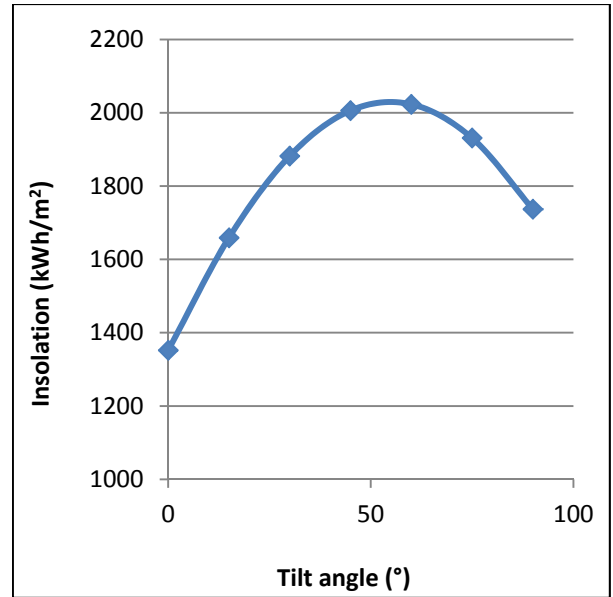


Figure 3.3 Yearly mean daily irradiation of a single-axis tracking system tilted at various angles in Montreal

3.2.1 Annual analysis

These systems have been studied in a typical year and the results are summarized in Table 3.3. The dual-axis tracking system is optimum. Annual analysis shows an increase of incident solar energy of 18%, 51%, and 57% for tilted, single-axis tracking, and dual-axis tracking arrays, respectively, as compared to the horizontal one. The total energy production of systems as compared to the horizontal array is 22%, 60%, and 66% more for tilted, single-axis tracking, and dual-axis tracking systems, respectively. The incident solar energy percentage increase is not equal to energy production percentage increase since the correlation between irradiation and relative efficiency of the PV system is not linear.

Dual-axis tracking and single-axis tracking arrays have the highest efficiencies among these systems. The annual efficiencies are 13.1% and 13.6% for the horizontal and tilted arrays, respectively, while the single-axis and dual-axis tracking systems have the same efficiency of 13.9%.

Table 3.3 Summarized results of annual analysis for Montreal

	Specification	Incident solar energy (MWh)	Energy produced (MWh)	System efficiency (%)	Array efficiency (%)	Inverter efficiency (%)	Specific annual yield (kWh/kW _p)
System	A	124.8	16.3	13.1	13.9	94.3	1135
	B	147.3	20.0	13.6	14.3	94.7	1387
	C	188.7	26.2	13.9	14.6	95.3	1817
	D	195.8	27.1	13.9	14.6	95.4	1885

Figure 3.4 shows the arrays incident solar energy over a year. Dual-axis tracking PV array absorbs more radiation than other arrays but it has almost the same performance as single-axis tracking system. The incident solar energy on tilted array is considerably higher than on horizontal one, except in summer since the sun moves across the sky through a path nearly overhead and a horizontal plane is perpendicular to the direct radiation. In fact, since we are located above the tropic, we cannot set a perfect alignment. We observed in November and December, the minimum amount of radiation, while the average of electricity consumption arises in winter. However, during December, January, and February, when the surrounding environment of arrays is covered by snow, arrays incident solar energy is increased considerably in all systems except the horizontal one. Reflected radiation from the ground covered by snow caused an incident solar energy increase upon those systems. An albedo factor of 0.8 has been assumed during the winter. Note that snow may start earlier than December and last after March in the Montreal area, thus increasing the gain due to the high albedo of snow. Besides, fresh snow has an albedo of 0.9 up to 0.95. Here, a conservative value of 0.8 is used to account for variations in the quality of snow and snow removal in some areas. The horizontal array is not sensitive to the change in the environment because it is facing the sky and therefore cannot absorb any radiation reflected from the ground. As it can be seen from the figure, there is a steep decrease in irradiance and electricity generation

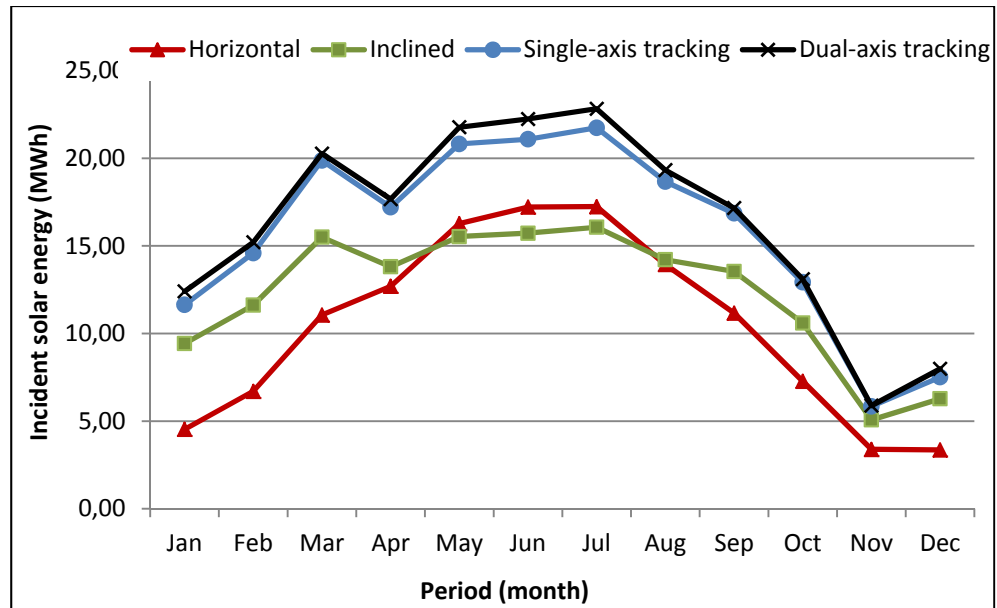


Figure 3.4 Annual incident solar energy upon systems in Montreal

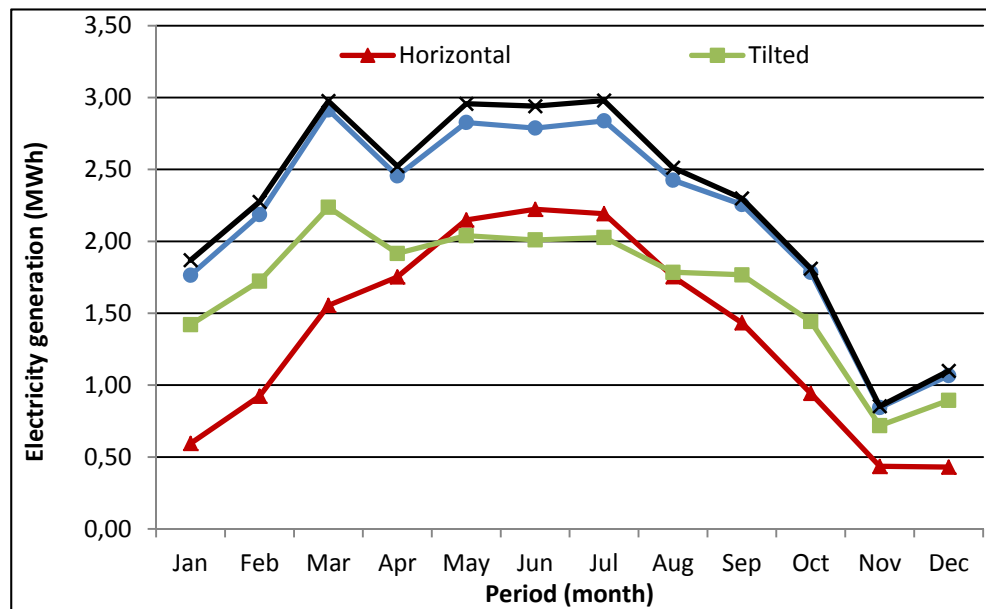


Figure 3.5 Annual electricity generation in Montreal

of tilted and tracking systems in April, because of the low albedo and many cloudy days during this month. However, there is often snow on the ground in April that can offset this decrease.

3.2.2 Analysis for a clear winter day

Figure 3.6 shows the incident solar energy for a clear day in winter, near the solstice (a very short day in Montreal). As it can be seen from the graph, the dual axis tracker receives more radiation than the others. Daily analysis shows an increase of array incident solar energy of up to 132%, 194%, and 214% for inclined, single-axis tracking, and dual-axis tracking arrays, respectively, as compared to the horizontal one. Figure 3.7 presents the electricity production of the systems during the clear winter day.

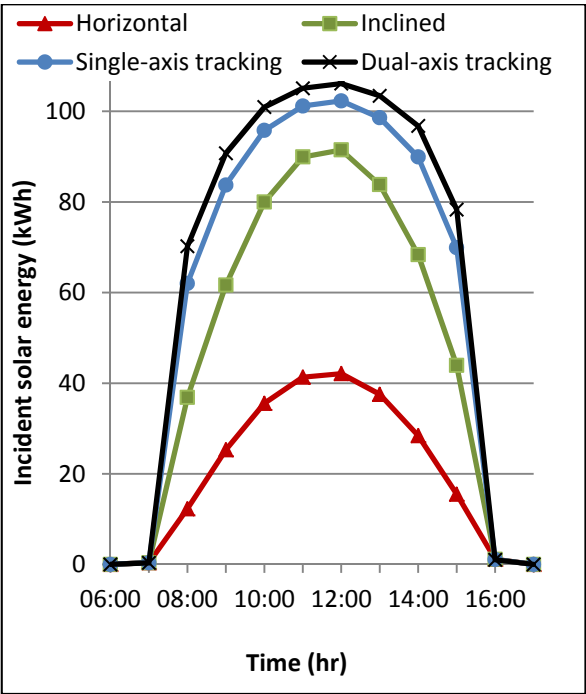


Figure 3.6 Hourly incident solar energy during a clear winter day in Montreal

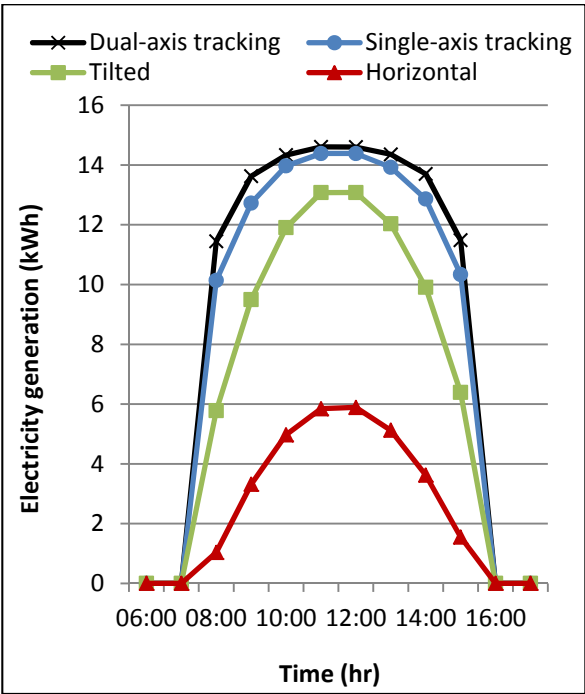


Figure 3.7 Electricity generation during a clear winter day in Montreal

3.2.3 Analysis for a clear summer day

A warm summer day with high intensity of radiation was selected to study these systems. Figure 3.8 and Figure 3.9 show incident solar energy and electricity generation during a clear day in summer. Here again, the dual-axis tracking system receives more radiation. The single-axis tracking array absorbs almost the same amount of radiation as the dual-axis tracking array, but at noon, when the sun is almost overhead in the sky, it has the lowest performance since the module is not perpendicular to solar beam radiation. In a clear summer day, the fixed systems receive almost the same amount of radiation, but the horizontal one receives 7% more radiation than the tilted one. This analysis shows an increase of array incident solar energy of up to 38% and 44% for single-axis tracking and dual-axis tracking arrays, respectively, as compared to the horizontal one.

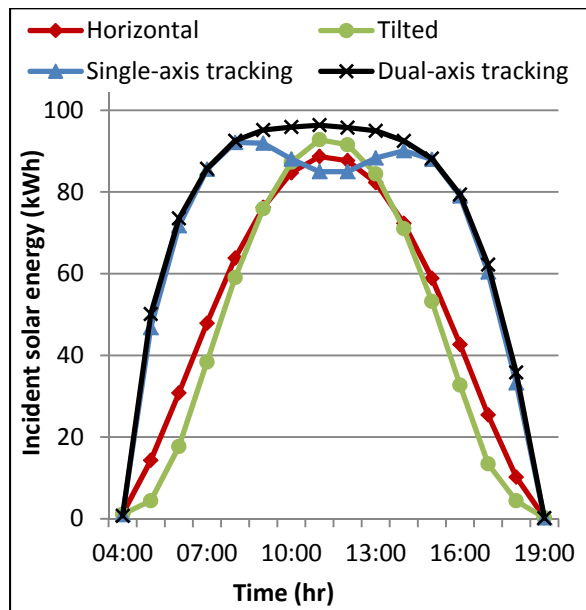


Figure 3.8 Hourly incident solar energy during a clear summer day in Montreal

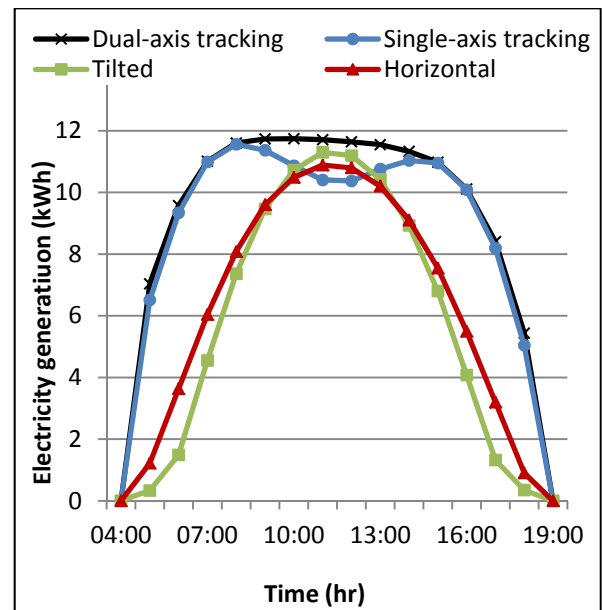


Figure 3.9 Electricity generation during a clear summer day in Montreal

3.2.4 Analysis for an overcast day

Figure 3.10 and Figure 3.11 show the hourly incident solar energy and electricity production during an overcast day in which the major part of the radiation is diffuse. The specific irradiation in overcast days is almost 10% of the specific irradiation in clear days. On a cloudy day, these systems have almost the same performance and the horizontal position is optimum. The horizontal system receives 9 kWh more solar energy and produces 1.5 kWh more electricity than the dual-axis tracking system in one day. Here, one has to be careful when it comes to comparing clear and overcast days. On a clear day, all systems are found to produce more than 10 kWh between 10am and 2 pm. On an overcast day, all systems produce 1 kWh between 11 am and 1 pm. The amount is 10 times less and the duration twice as short.

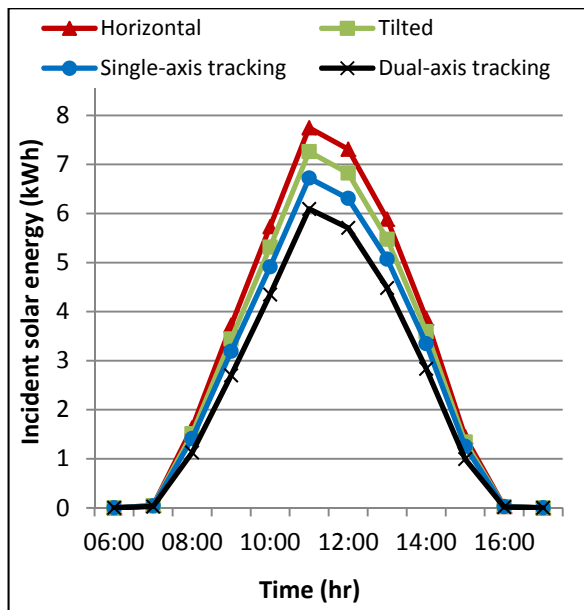


Figure 3.10 Hourly incident solar energy during an overcast day in Montreal

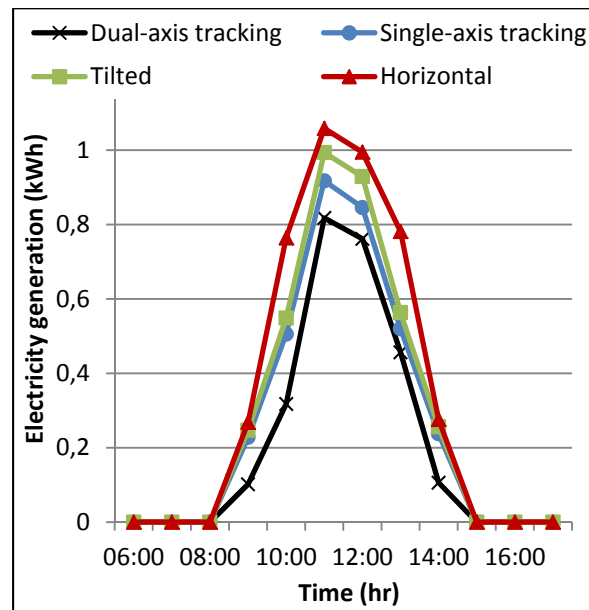


Figure 3.11 Electricity generation during an overcast day in Montreal

3.2.5 Modules temperature analysis

In the severe weather conditions of Montreal, large amount of snow could be accumulated on PV modules over a winter night. This phenomenon would cause a delay in starting the process of electricity production by PV panels in the morning. When the sun rays strike the panels, two heat sources help melting the ice or snow: solar radiation and heat produced by the PV cells as they produce electricity. As soon as a small area of PV panel isn't covered by snow, it absorbs solar radiation, melts snow, and produces electricity. In the morning, when the sun shines, the tracking PV system is conveniently perpendicular to the sun rays when the layer of snow or ice melts gradually. Figure 3.12 shows the ambient and module temperature of different systems in a winter day. It is assumed that systems are not covered by snow.

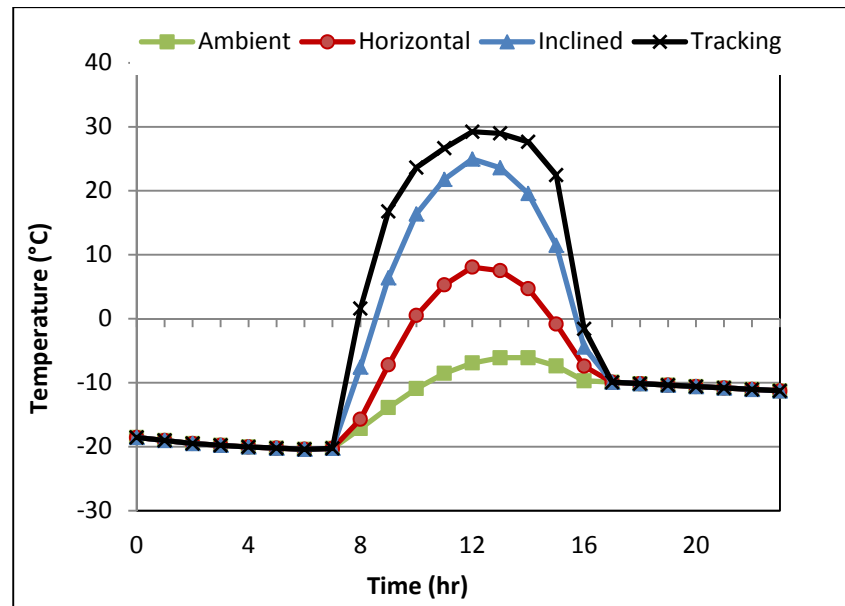


Figure 3.12 Ambient and module temperature variation with time during a day in Montreal

As it can be seen in Figure 3.12 the module temperature for a cold day differ very significantly. When the ambient temperature is -17°C at 8 am, the temperatures of the horizontal, tilted, and dual-axis tracking systems are -15°C , -7°C , 1.6°C , respectively. Only

one hour later, the temperature of the PV module installed on a dual-axis tracking system will be increased to 16°C while the ambient temperature is -13°C (at 9 am). This is one of the most interesting advantages of solar tracking systems in northern climates that, to the best knowledge of the author, has never been discussed in previous researches. Here, one can clearly understand that a thin layer of snow or frost would fall from the module before 9 am.

3.2.6 Albedo effect

Reflected radiation from the ground, covered by snow, affects the amount of arrays irradiance. In solar energy systems, this reflected radiation from the surrounding of the modules, except from the atmosphere itself, is accounted via the so-called albedo. Basically, the albedo factor value is between 0 and 1. No reflection implies that the albedo is zero while a unit albedo indicates that the surroundings reflect all incident radiation. Fresh snow has an average albedo of 0.8-0.9 for solar radiation. In this work, it is assumed that in December, January, February, and March, the ground is covered by snow in Montreal and that the average albedo is 0.8. Figure 3.13 shows the electricity generation during two winters, with high albedo (0.8) and with low albedo (0.2). The results of simulations show that reflected radiation from the snow causes an increase of 4.1%, 5.6%, and 6.9% in electricity generation over the whole winter for inclined, single-axis tracking, and dual-axis tracking systems, respectively. Therefore the reflected radiation from the snow in northern climate countries like Canada is not negligible.

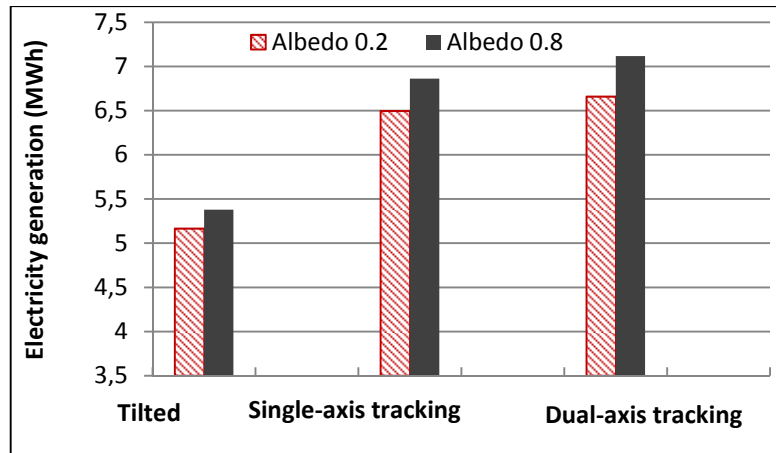


Figure 3.13 Electricity production of the systems over two winters in Montreal

Furthermore, the results suggest that the increase in electricity generation reinforces the advantages of tracking strategies. Finally, the results also indicate that even in a partly or unevenly covered ground, (simulated here with a low albedo of 0.2) reflected solar radiation increase the performances. Thus, this suggests that the increase would be significant not only in rural but also in urban areas.

3.3 Case II: Casablanca

Case study II is located in Casablanca, Morocco, with latitude and longitude of 33°36'N and 7°36'W, respectively. Casablanca is located in a very mild Mediterranean climate which is affected by cool Atlantic Ocean currents. Casablanca has relatively small temperature fluctuations during a year, with average high temperature of 21.2°C and average low temperature of 13.6°C (World Weather Information Office, 2011). As for case I, system A is oriented horizontally and system D is a dual-axis tracking. System B is tilted at yearly optimum angle which is equal to 30° in Casablanca (Figure 3.14). System C is a single-axis tracking system for which modules are tilted at 50°: the optimum tilt angle for Casablanca. Recalling Figure 3.2, one can clearly recognize the differences between the best tilt angle in Montreal (40°) and Casablanca (30°) for the fixed tilted system. This difference is less for the single-axis tracking systems: 55° in Montreal and 50° in Casablanca.

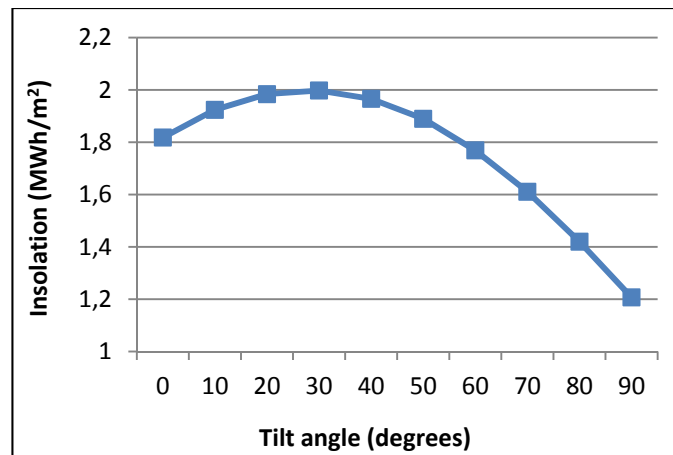


Figure 3.14 Yearly mean daily insolation of a module tilted at various angles in Casablanca

3.3.1 Annual analysis

The important results from yearly simulations are summarized in Table 3.4.

Table 3.4 Summarized results of annual analysis for Casablanca

	Specification	Incident solar energy (MWh)	Energy produced (MWh)	System efficiency (%)	Array efficiency (%)	Inverter efficiency (%)	Specific annual yield (kWh/kW _p)
System	A	167.8	21.2	12.7	13.3	95.0	1476
	B	184.4	23.6	12.8	13.5	95.1	1640
	C	231.8	30.3	13.1	13.7	95.6	2103
	D	240.9	31.5	13.1	13.7	95.6	2186

As it can be seen from the Table 3.4, dual-axis tracking system is the optimum system. Annual analysis shows an increase of array incident solar energy of up to 10%, 38.1%, and 43.5% for tilted, single-axis tracking, and dual-axis tracking arrays, respectively, as compared to the horizontal system. The annual efficiencies are 12.7% and 12.8% for the

horizontal and tilted systems, while tracking systems have 13.1% efficiency. This annual efficiency is lower in Casablanca than in Montreal because of the higher ambient temperature in this location. The annual average ambient temperature in Casablanca is about 10°C higher than in Montreal which reduces the efficiency of PV modules (0.5% per each °C).

The total energy production of systems as compared to the horizontal array are 10.8%, 42%, and 48% more for tilted, single-axis tracking, and dual-axis tracking systems, respectively. Figure 3.15 shows the arrays incident solar energy over a year. The dual-axis tracking PV array captures more radiation than other arrays. The incident solar energy on tilted array is higher than on horizontal one, except in summer. The curves trends are almost similar to the graph for Montreal. Since there is no snowfall in Casablanca there is no increase in incident solar energy in winter.

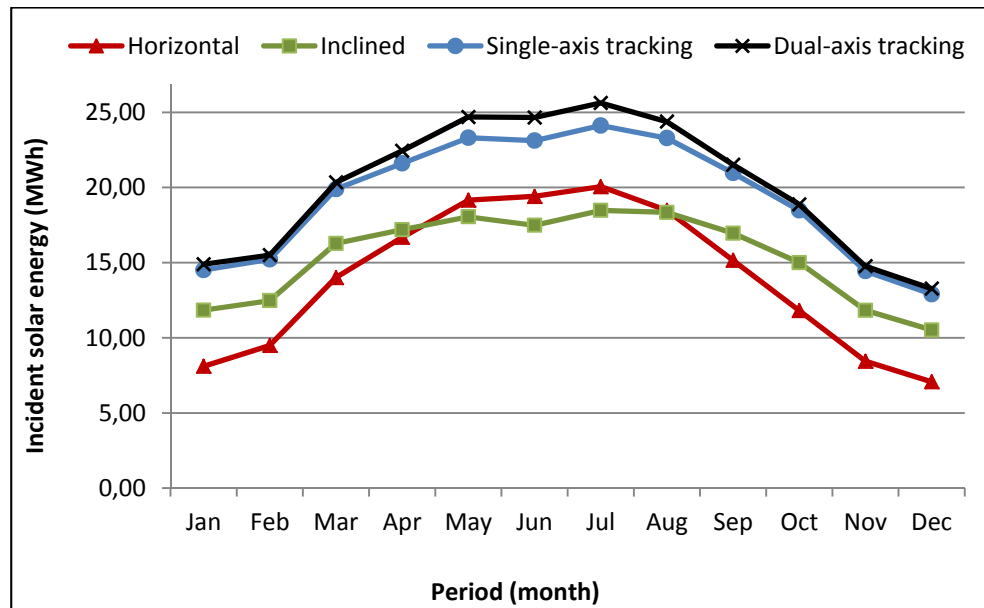


Figure 3.15 Annual incident solar energy in Casablanca

3.3.2 Analysis for a clear winter day

Figure 3.16 shows the arrays incident solar energy for a clear day in winter. As it can be seen from the graph, the dual axis tracking and single-axis tracking systems receive almost equal amounts of radiation. Daily analysis shows an increase of array incident solar energy of up to 41.5%, 83.4%, and 89% for tilted, single-axis tracking, and dual-axis tracking arrays, respectively, as compared to the horizontal one. The differences in tracking strategies are less than those for Montreal (Figure 3.6). It is worth noting that the maximum hourly incident solar energy in each case (Montreal and Casablanca) is in the same order of magnitude (100 kWh at noon) but a typical winter day in Casablanca is longer (production from 7am till 6pm in Casablanca compared to production from 8am till 5pm in Montreal).

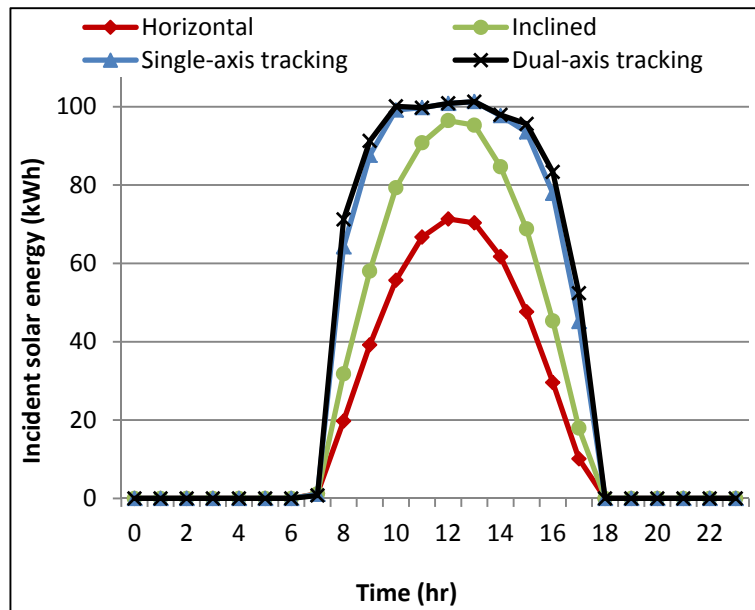


Figure 3.16 Hourly incident solar energy during a clear winter day in Casablanca

3.3.3 Analysis for a clear summer day

Figure 3.17 shows arrays incident solar energy during a clear day in summer. The dual-axis tracking system receives more radiation. The single-axis tracking array receives almost the same amount of radiation as the dual-axis tracking array, but at noon, when the sun is overhead at the sky, it has the lowest performance. In a clear summer day, the fixed systems also receive almost the same amount of radiation. Daily analysis shows an increase of array incident solar energy of up to 25.3% and 33.5% for single-axis tracking and dual-axis tracking arrays, respectively, as compared to the horizontal array. The tilted system receives 9.5% less radiation than the horizontal system.

In terms of comparison, it is interesting to report the differences between Montreal and Casablanca. The obvious difference is that the total day time is longer in Montreal in summer as it is 12° further north. However, the impressive difference is that a comparison between Figure 3.8 and Figure 3.17 shows that the dual-axis tracking system operating in Montreal receives 13.5% more solar energy than the system operating in Casablanca.

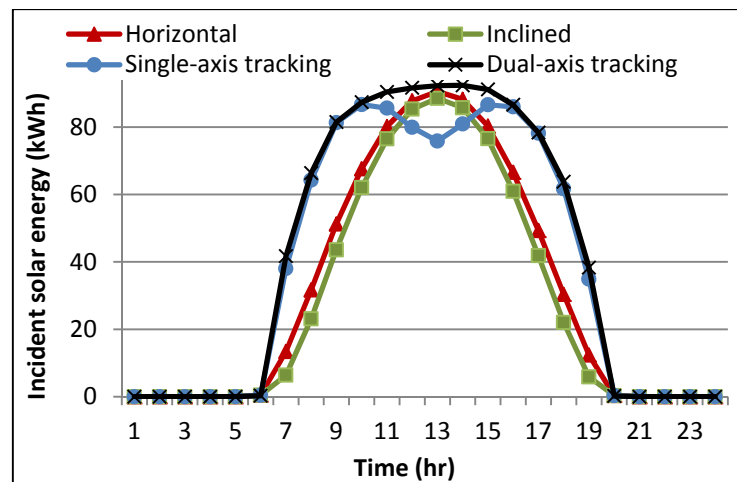


Figure 3.17 Hourly incident solar energy during a clear summer day in Casablanca

3.3.4 Analysis for an overcast day

Figure 3.18 shows the incident solar energy during an overcast day in Casablanca. Here again, the PV systems receive almost similar amounts of radiation in overcast conditions. The horizontal system receives more radiation than others. All the overcast days selected in this study are winter days. The horizontal system receives 11 kWh more solar energy and produces 2 kWh more electricity than the dual-axis tracking system. The specific radiation during this overcast day is 10% of the radiation during a clear day.

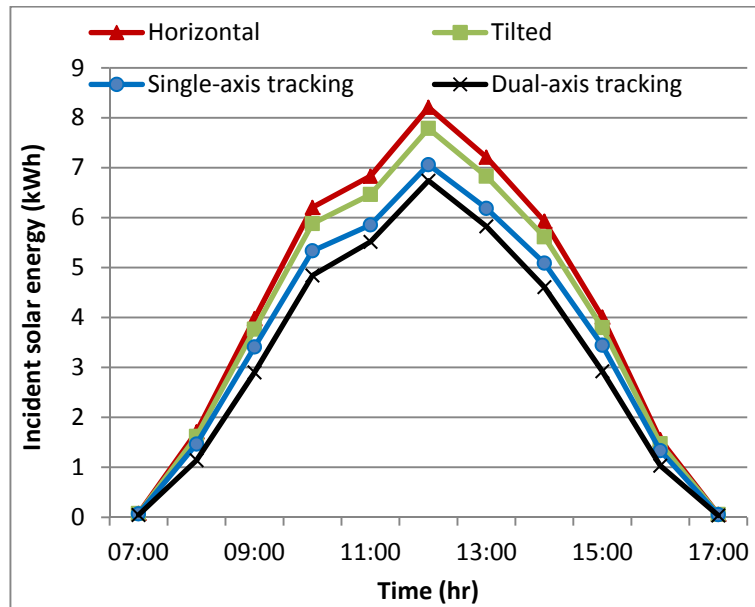


Figure 3.18 Hourly incident solar energy during an overcast day in Casablanca

3.3.5 Modules temperature analysis

Since there is no snowfall in Casablanca, the interesting effect of solar tracking on module temperature for snow melting is not present in Casablanca. In fact, increasing temperature reduces the efficiency of modules. This is an advantage for Montreal as compared to Casablanca. In Figure 3.19, both tracking systems have the same temperature throughout the

day. Trends are smaller than those observed in Figure 3.12 for Montreal but a significant increase is observed for temperatures in the afternoon. The efficiency threshold for best efficiency is basically 25°C. Figure 3.19 shows that for the most hours of a day the modules operate with an impaired efficiency in Casablanca.

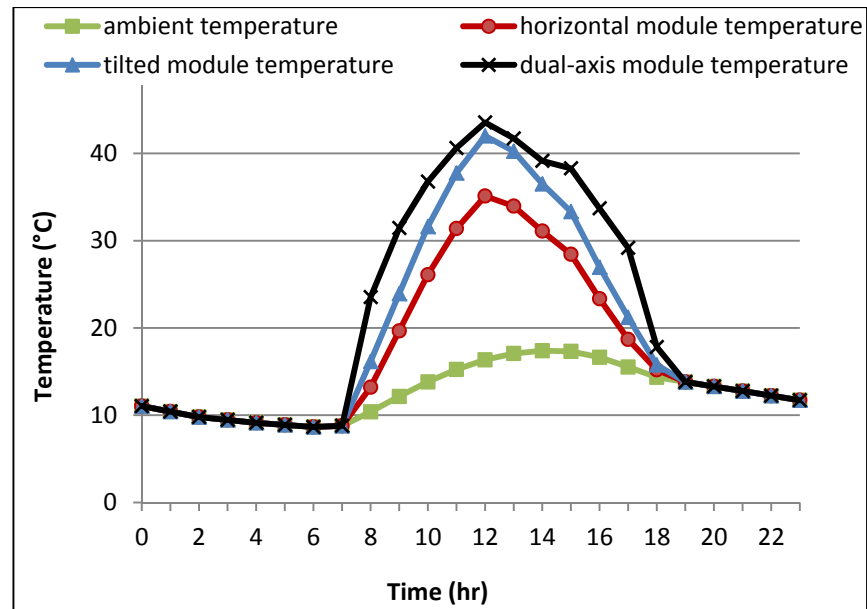


Figure 3.19 Ambient and module temperature variation with time during a day in Casablanca

3.4 Case III: Ouagadougou

This case study concerns the capital of Burkina Faso, Ouagadougou, which is located at latitude and longitude of 12°20'N and 1°31'W, respectively. Ouagadougou's climate is hot with the rainfall of 900mm per year. The average high temperature is 35.4°C and the average low temperature is 22.1°C (climate-zone). In Ouagadougou, the yearly optimum tilt angle for a PV system is 15° and the optimum tilt angle for a single-axis tracking system is 40°. These values are considerably lower than the corresponding angles for Montreal.

3.4.1 Annual analysis

Simulations have been carried out for the above-mentioned four systems in a typical year and the results are illustrated in Table 3.5.

Table 3.5 Summarized results of annual analysis for Ouagadougou

	specification	Incident solar energy (MWh)	Energy produced (MWh)	System efficiency (%)	Array efficiency (%)	Inverter efficiency (%)	Specific annual yield (kWh/kW_p)
System	A	202.7	24.4	12.0	12.7	95.2	1696
	B	207.8	25.1	12.1	12.7	95.2	1740
	C	253.5	31.2	12.3	12.9	95.5	2165
	D	264.1	32.5	12.3	12.9	95.6	2260

Here again, the dual-axis tracking system is the most efficient system over a year. Annual analysis shows an increase of array incident solar energy of up to 2%, 25%, and 30% for tilted, single-axis tracking, and dual-axis tracking arrays, respectively, as compared to the horizontal array. Comparison with Table 3.3 indicates that the differences between systems are much higher in Montreal than in Ouagadougou. On the other hand, the incident solar energy varying from 202 to 264 MWh per year, in Ouagadougou is always- as expected- higher than in Montreal (from 125 to 196 MWh) but the array efficiency is always better in Montreal than in Ouagadougou for the four systems considered here. The total energy production of systems as compared to the horizontal array are 2%, 27%, and 32.5% for tilted, single-axis tracking, and dual-axis tracking systems, respectively.

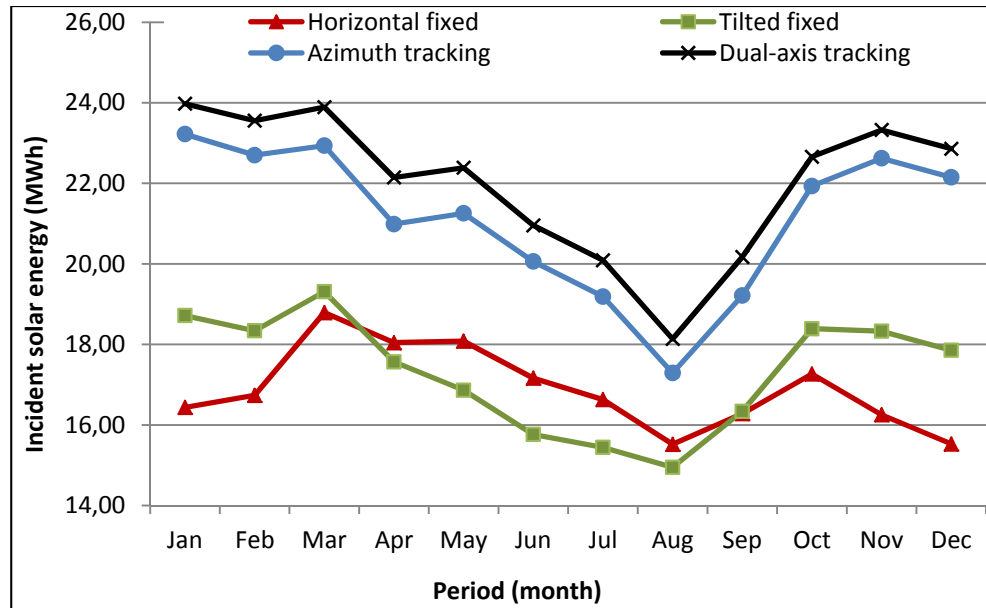


Figure 3.20 Annual incident solar energy upon systems in Ouagadougou

Figure 3.20 shows the arrays incident solar energy over a year. The trends of these curves are considerably different from the systems located either in Montreal or in Casablanca. The dual-axis tracking PV array absorbs more radiation than other arrays but it has almost the same performance as single-axis tracking PV array. The irradiance on tilted array is higher than that on the horizontal one, except between April and September. The minimum intensity of solar radiation is occurring in August in Ouagadougou.

3.4.2 Analysis for a clear winter day

Figure 3.21 shows the arrays incident solar energy for a clear day in winter. As it can be seen from the graph, the dual axis tracking and single-axis tracking systems receive almost equal amounts of radiation. Daily analysis shows an increase of array incident solar energy of up to 9.3%, 37.7%, and 43.7% for tilted, single-axis tracking, and dual-axis tracking arrays, respectively, as compared to the horizontal one. There is more radiation at noon in a winter day in Montreal (Figure 3.6) than in Ouagadougou despite the long path of direct radiation through the atmosphere.

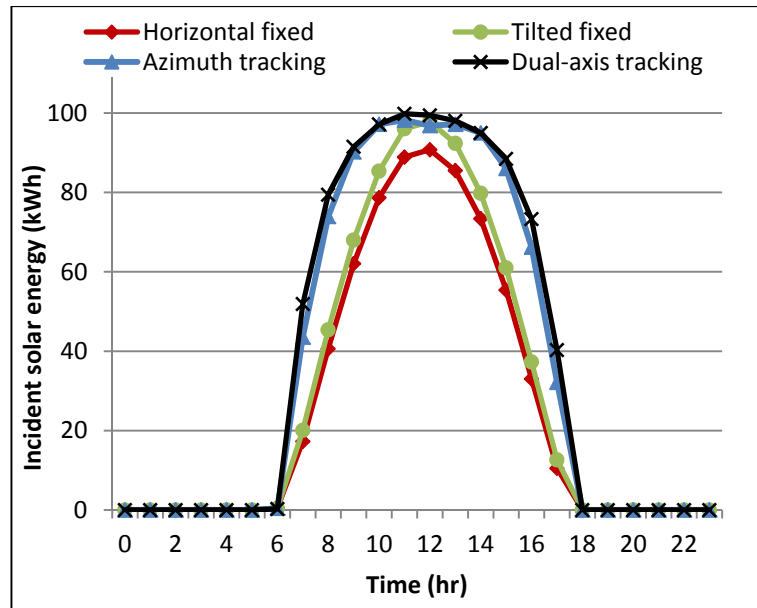


Figure 3.21 Hourly incident solar energy during a clear winter day in Ouagadougou

3.4.3 Analysis for clear summer day

Figure 3.22 shows arrays incident solar energy during a clear day in summer. Here, both tracking systems receive more radiation. At noon, the single-axis tracking has lower performance. In a clear summer day, the fixed systems also receive almost the same amount of radiation. Daily analysis shows an increase of array incident solar energy of up to 18.5% and 24.8% for single-axis tracking and dual-axis tracking arrays, respectively, as compared to the horizontal array. The tilted system receives 11.7% less radiation than the horizontal system.

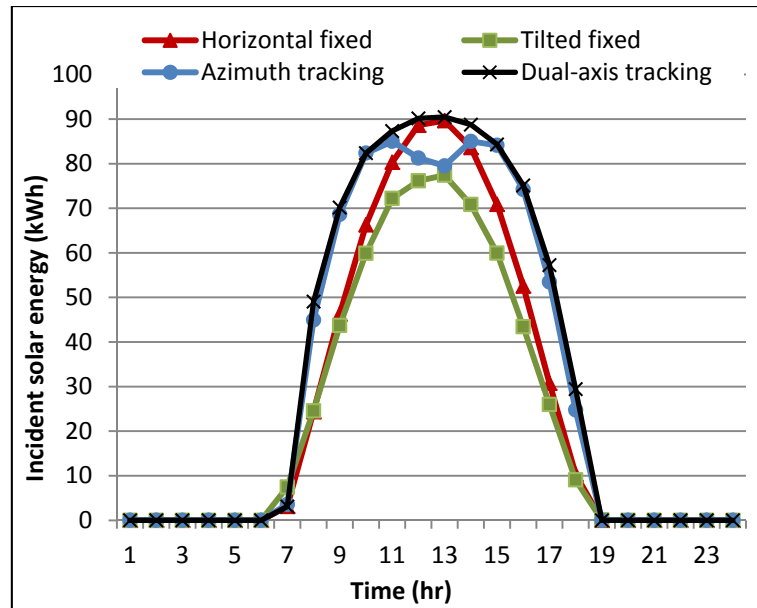


Figure 3.22 Hourly incident solar energy during a clear summer day in Ouagadougou

3.4.4 Analysis for an overcast day

Figure 3.23 shows the array incident solar energy in an overcast day in which the major part of the radiation is diffuse. On a cloudy day, these systems have almost the same performance and the horizontal position is optimum while the single-axis tracking has the lowest performance. The selected is one of the cloudiest days in Ouagadougou, but it is not as cloudy as the overcast day in Montreal. Therefore, the amount of hourly incident solar energy in Ouagadougou is almost 4 times more than these values in Montreal.

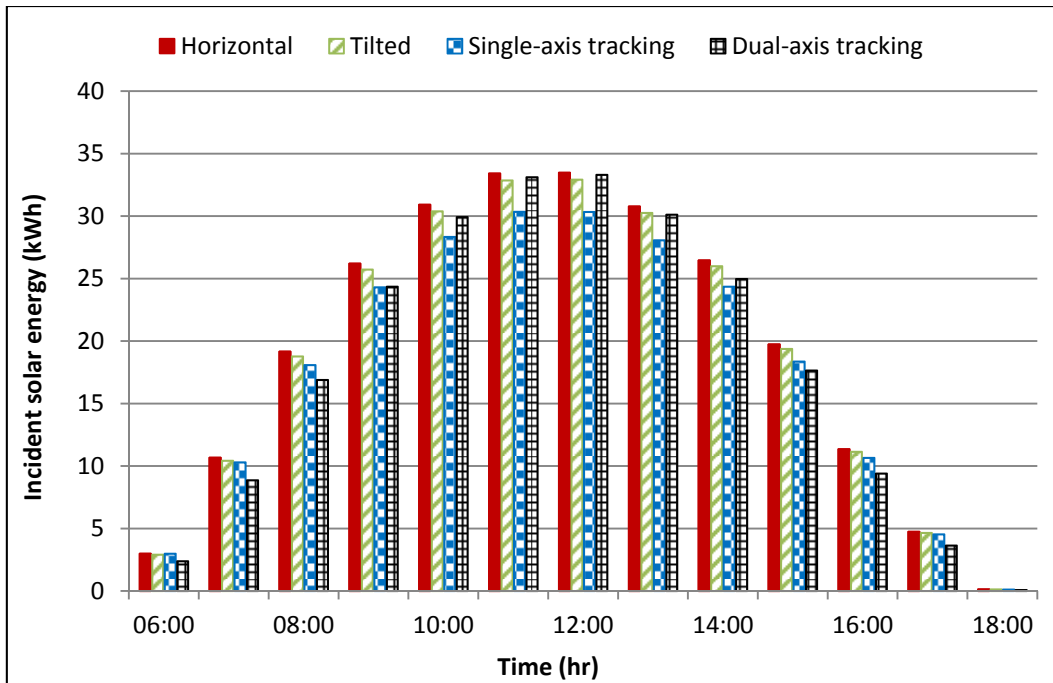


Figure 3.23 Hourly incident solar energy during an overcast day in Ouagadougou

3.4.5 Modules temperature analysis

The modules temperature reaches 60°C in Ouagadougou which reduces 15% the modules efficiency approximately. Figure 3.24 shows the ambient and modules temperature during a day in Ouagadougou. Dual-axis tracking modules have higher temperature for longer time compared to other systems.

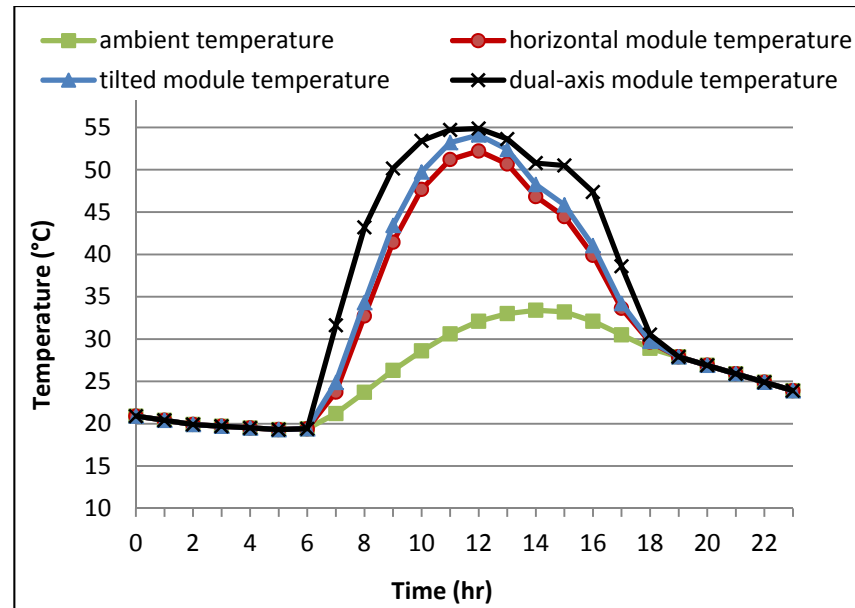


Figure 3.24 Ambient and module temperature variation with time during a day in Ouagadougou

3.5 Case IV: Olympia, Washington

The last case study concerns the capital of Washington State, Olympia, which is located at latitude and longitude of 47° N and $122^{\circ} 53' W$, respectively. Olympia's climate is an oceanic climate with a large amount of rainfall per year. Olympia is one of the cloudiest cities in the world. November and December are the rainiest months in Olympia. The yearly precipitation amount in Olympia is 1290 mm. The average high temperature is $15.4^{\circ}C$ and the average low temperature is $4.2^{\circ}C$ (Climate Zone, 2011). Olympia was selected in order to analyze the solar tracking PV systems in a cloudy location. In Olympia the yearly optimum tilt angle for a PV system is 30° and the optimum tilt angle for a single-axis tracking system is 50° .

3.5.1 Annual analysis

Simulations have been carried out for the four systems for a typical year and the results are summarized in Table 3.6.

Table 3.6 Summarized results of annual analysis for Olympia

	specification	Incident solar energy (MWh)	Energy produced (MWh)	System efficiency (%)	Array efficiency (%)	Inverter efficiency (%)	Specific annual yield (kWh/kW _p)
System	A	109.6	14.2	12.9	13.8	93.7	985.3
	B	121.7	16.0	13.1	14.0	94.0	1111
	C	147.6	19.9	13.4	14.2	94.7	1379
	D	150.7	20.3	13.5	14.2	94.8	1409

As it can be seen from the Table 3.6, dual-axis tracking system (system D) is optimum in all aspects. Annual analysis shows an increase of array incident solar energy of up to 11%, 34.7%, and 37.5% for tilted, single-axis tracking, and dual-axis tracking arrays, respectively, as compared to the horizontal array.

The total energy production of systems as compared to the horizontal array are 12.7%, 40.8%, and 43% for tilted, single-axis tracking, and dual-axis tracking systems, respectively. Although Olympia is located at the same latitude as Montreal, the results show 13% to 30% more incident solar energy for Montreal compared to Olympia. The PV systems in Montreal produce 15% to 35% more electricity than the systems in operating in Olympia. In terms of energy produced by the dual-axis tracking system, the specific annual yield for Montreal is 25% more than that in Olympia.

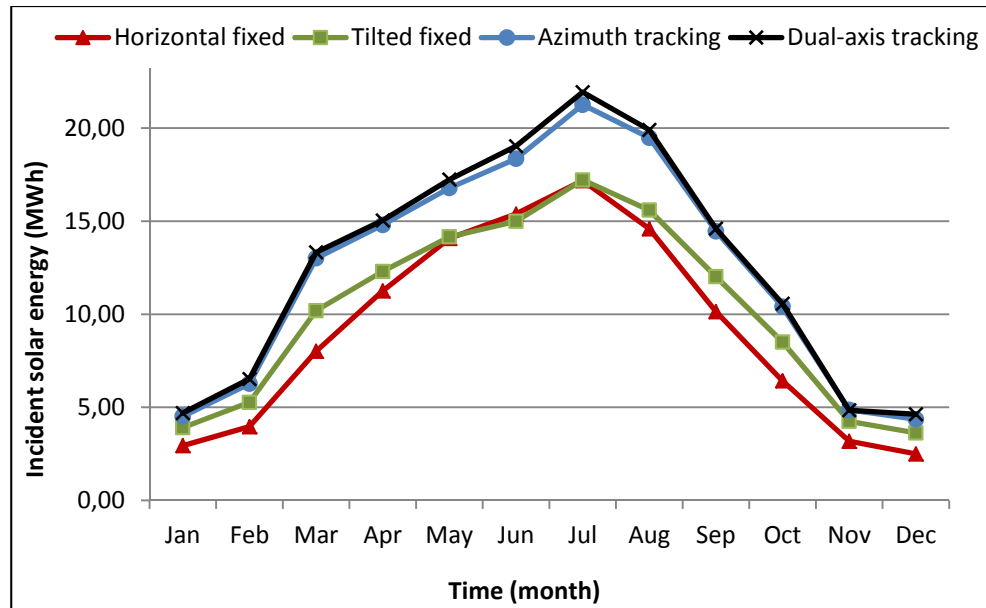


Figure 3.25 Annual incident solar energy upon systems in Olympia

Figure 3.25 shows the arrays incident solar energy over a year. Dual-axis tracking PV array absorbs more radiation than other arrays but it has almost the same performance as single-axis tracking PV array. The incident solar energy on tilted array is higher than on horizontal one almost over the year. There is an irradiation peak for all these systems in July because of the geographical reasons.

3.5.2 Analysis for a clear winter day

Figure 3.26 shows the arrays incident solar energy for a clear day in winter. As it can be seen from the graph, the dual axis tracking and single-axis tracking systems receive almost equal amounts of radiation. Daily analysis shows an increase of array incident solar energy of up to 83%, 147%, and 167.8% for tilted, single-axis tracking, and dual-axis tracking arrays, respectively, as compared to the horizontal one.

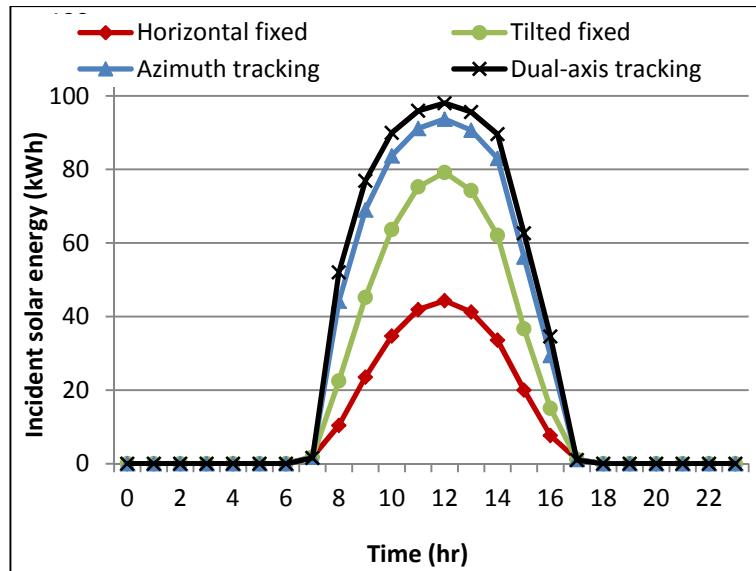


Figure 3.26 Hourly incident solar energy during a clear winter day in Olympia

3.5.3 Analysis for a clear summer day

Figure 3.27 shows arrays incident solar energy during a clear day in summer. Here, the dual-axis tracking system receives more radiation but not a considerable amount. The single-axis tracking array absorbs almost the same amount of radiation as the dual-axis tracking array, but at noon, when the sun is overhead at the sky, it has the lowest performance. In a clear summer day, the fixed systems also receive almost the same amount of radiation. Daily analysis shows an increase of array incident solar energy of up to 1%, 38.2%, and 42.8% for tilted, single-axis tracking, and dual-axis tracking arrays, respectively, as compared to the horizontal array.

3.5.4 Analysis for an overcast day

Figure 3.28 shows the array incident solar energy in an overcast day in which the major part of the radiation is diffuse. On a cloudy day, these systems have almost the same performance

and the horizontal position is optimum while the dual-axis tracking has the lowest performance.

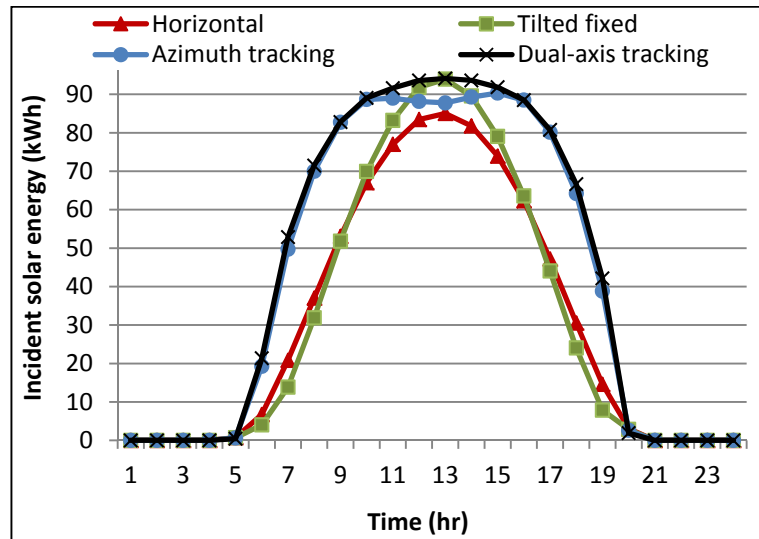


Figure 3.27 Hourly incident solar energy during a clear summer day in Olympia

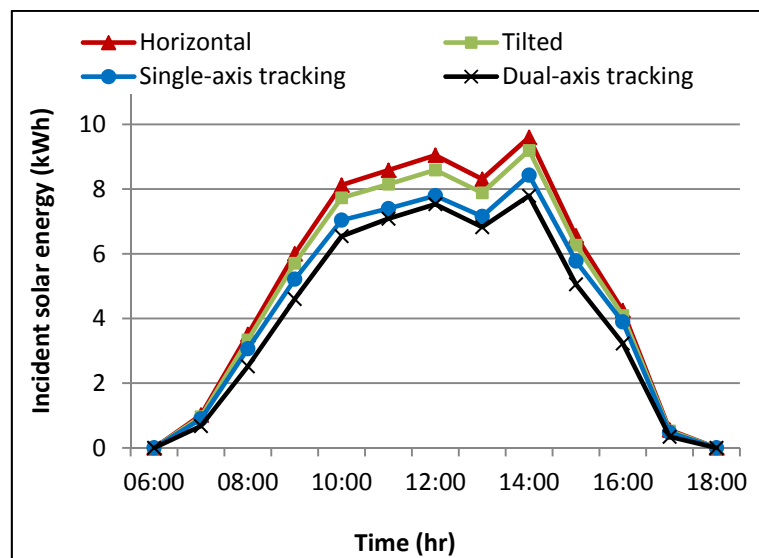


Figure 3.28 Hourly incident solar energy during an overcast day in Olympia

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the summary of important results from the simulations. Section 4.1 explains the results of performance analyses of PV systems in different locations and different weather conditions. Section 4.2 describes the effect of solar tracking on modules temperature.

4.1 Performance analysis

According to the results obtained from numerous simulations, arrays incident solar energy depends not only on the system location but also upon system orientation. Furthermore, arrays incident solar energy improvement by tracking the sun is found not to be equal in all locations. In Montreal, tracking the sun causes a larger increase in arrays incident solar energy as compared to other locations. In Olympia tracking the sun causes the minimum increase among other locations due to oceanic climate conditions.

Table 4.1 Relative annual incident solar energy (%) upon various orientations compared to the fixed tilted system

Configuration	Montreal	Casablanca	Ouagadougou	Olympia
Horizontal	-15%	-9%	-2.5%	-10%
Single-axis tracking	28%	26%	22%	21%
Dual-axis tracking	33%	31%	27%	24%

As it can be seen from the Table 4.1 solar tracking PV systems have the highest performances among other systems. Although dual-axis tracking systems have better performance than single-axis tracking systems, it is also more complicated and expensive. Table 4.2 shows the electricity production of different systems as compared to tilted one. As it was mentioned before, the arrays incident solar energy percentage increase is not equal to

electricity production percentage increase since the correlation between incident solar energy and relative efficiency of PV systems is not linear.

Table 4.2 Relative electricity production (%) of different systems as compared to the fixed tilted system

Configuration	Montreal	Casablanca	Ouagadougou	Olympia
Horizontal	-18%	-10%	-2%	-11%
Single-axis tracking	31%	28%	25%	25%
Dual-axis tracking	36%	33%	30%	27%

As it can be seen from Table 4.2 dual-axis tracking systems produce more electricity than the others. A dual-axis tracking system in Montreal produces 1 MWh (3.8%) more electricity than the single-axis tracking system over a year. The own consumption of trackers has not been considered. Selecting between single-axis tracker and dual-axis tracker for a PV system depends preponderantly on own consumption of trackers, the project budget, the cost of electricity, etc.

4.2 Tracking advantage

In this section, the tracking advantage for each situation is computed and analyzed. The equations to find the tracking advantage of dual-axis tracker versus the horizontal and tilted systems are presented. Equations of 4.1 and 4.2 present the tracking advantage of dual-axis tracker versus the horizontal and tilted systems, respectively.

$$TA_{DT-H} = \frac{\left(1 - \frac{H}{DT}\right)}{\left(\frac{H}{DT}\right)} \quad (4.1)$$

$$TA_{DT-T} = \frac{\left(1 - \frac{T}{DT}\right)}{\left(\frac{T}{DT}\right)} \quad (4.2)$$

The tracking advantage of single-axis tracking system versus the horizontal and the tilted systems can be represented by

$$TA_{ST-H} = \frac{\left(1 - \frac{H}{ST}\right)}{\left(\frac{H}{ST}\right)} \quad (4.3)$$

$$TA_{ST-T} = \frac{\left(1 - \frac{T}{ST}\right)}{\left(\frac{T}{ST}\right)} \quad (4.4)$$

In equations 4.1 and 4.2, H is the electricity production of the horizontal system, T is the electricity production of tilted system, ST and DT repeated the same value for the single-axis and dual-axis tracking systems. These nomenclatures are straight forward for the equations 4.3 and 4.4 too.

4.2.1 Monthly tracking advantage

Figure 4.1 and Figure 4.2 show the monthly tracking advantages versus the horizontal and the tilted systems. In Figure 4.1 we observed significant larger tracking advantage during the winter. Furthermore, dual-axis tracking system has larger tracking advantage in all months. As it can be seen from Figure 4.2, the tracking advantage is superior during the summer.

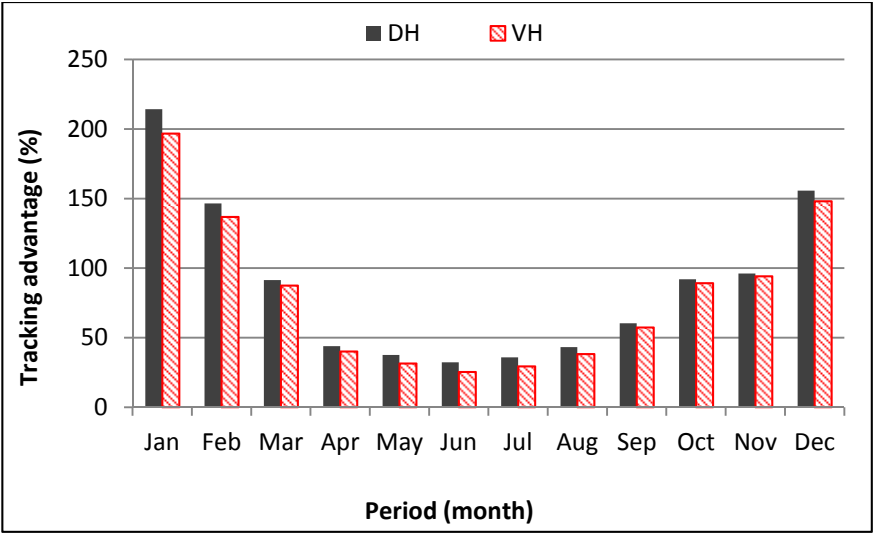


Figure 4.1 Monthly tracking advantage versus the horizontal system in Montreal

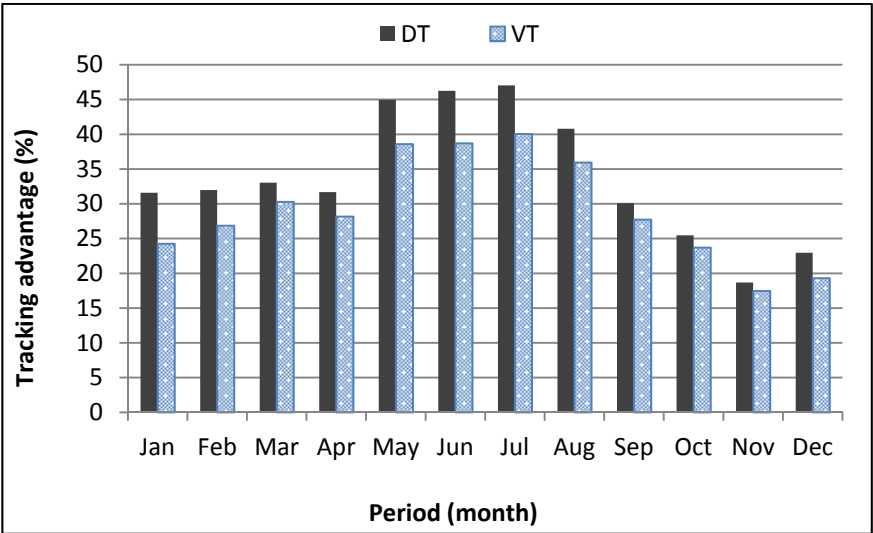


Figure 4.2 Monthly tracking advantage versus the tilted system in Montreal

4.2.2 Daily tracking advantage

Figure 4.3 and Figure 4.4 show the tracking advantage of dual-axis tracker and single-axis tracker versus the horizontal and the tilted systems, respectively. Near the sunrise and the sunset, the tracking advantage has a very large value since the fixed systems do not look toward the sun.

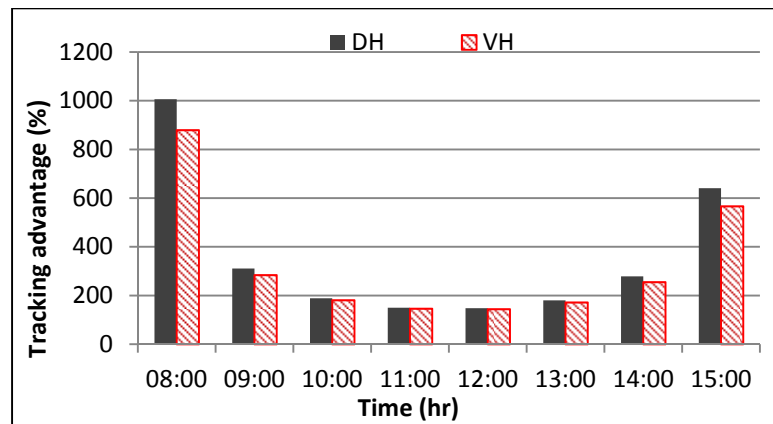


Figure 4.3 Tracking advantage versus the horizontal system during a clear winter day in Montreal

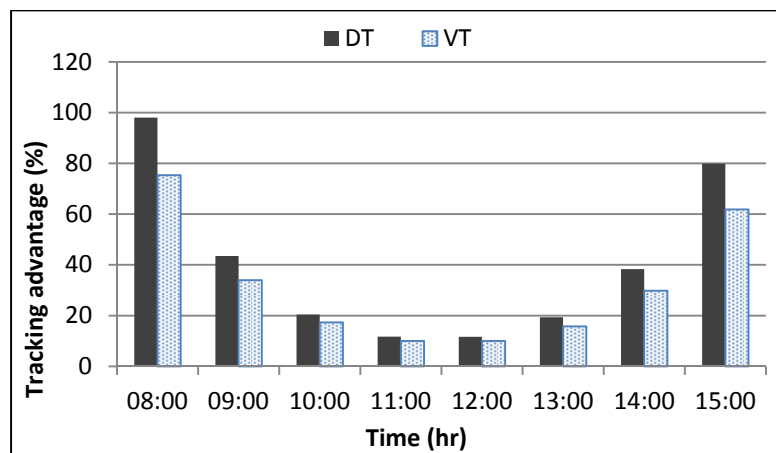


Figure 4.4 Tracking advantage versus the tilted system during a clear winter day in Montreal

Figure 4.5 and Figure 4.6 show the tracking advantage versus horizontal and tilted positions during a clear summer day. At the beginning and the end of the day tracking advantage has a large value, while around the noon the tracking advantage is almost zero.

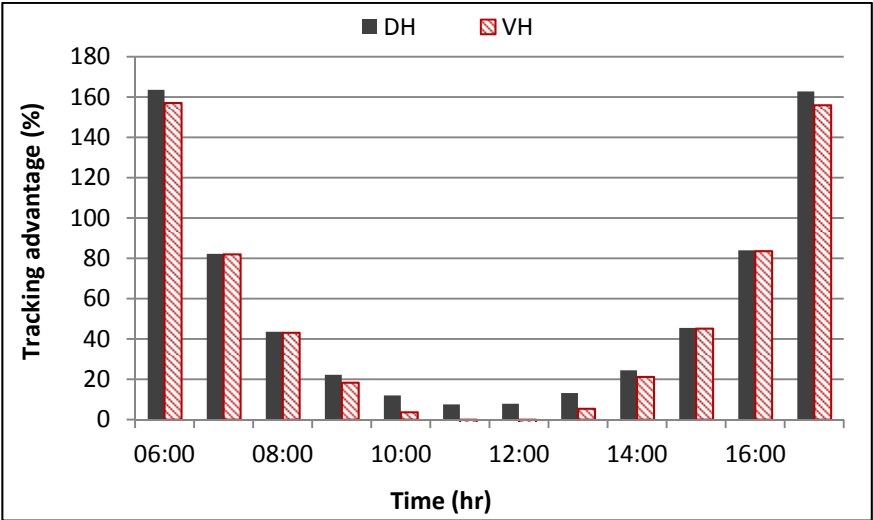


Figure 4.5 Tracking advantage versus the horizontal system during a clear summer day in Montreal

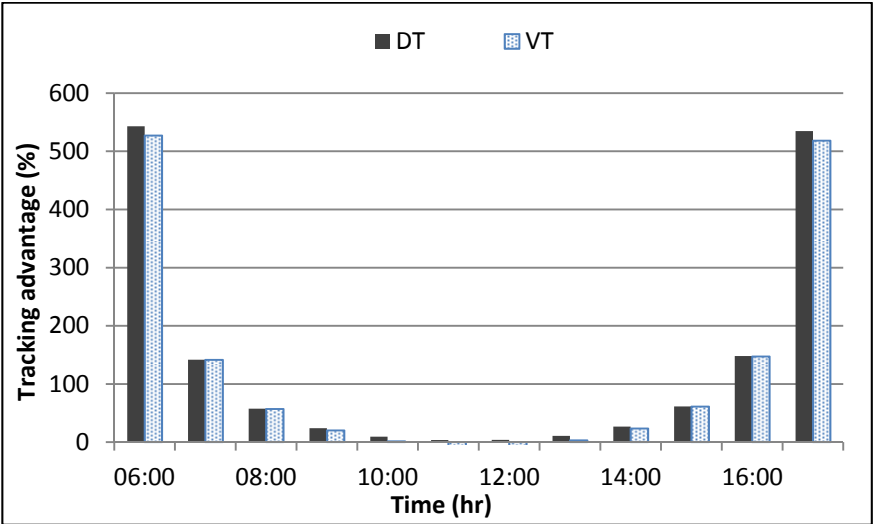


Figure 4.6 Tracking advantage versus the tilted system during a clear summer day in Montreal

Figure 4.7 and Figure 4.8 show the tracking advantage versus the horizontal and the tilted systems during an overcast day. In cloudy days, the tracking advantage is negative which means that tracking the sun is counterproductive in cloudy conditions. Horizontal position is the optimum position in overcast conditions, since the main part of the radiation is diffuse.

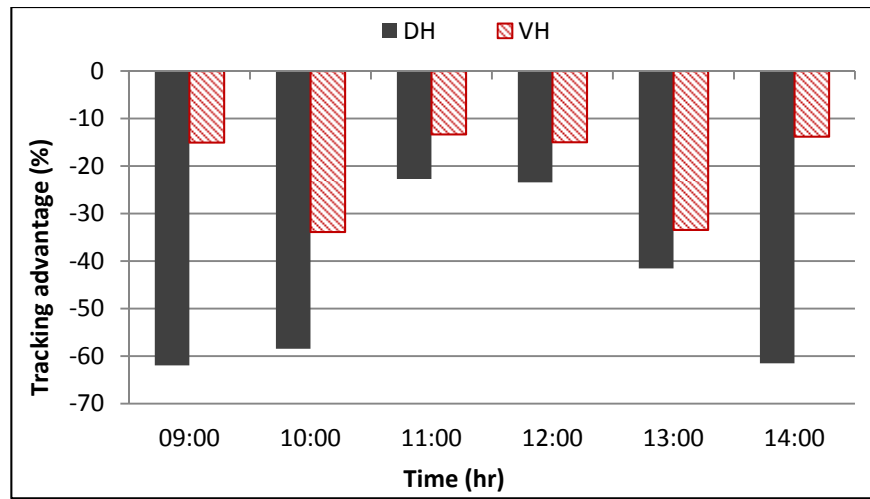


Figure 4.7 Tracking advantage versus the horizontal system during a cloudy day in Montreal

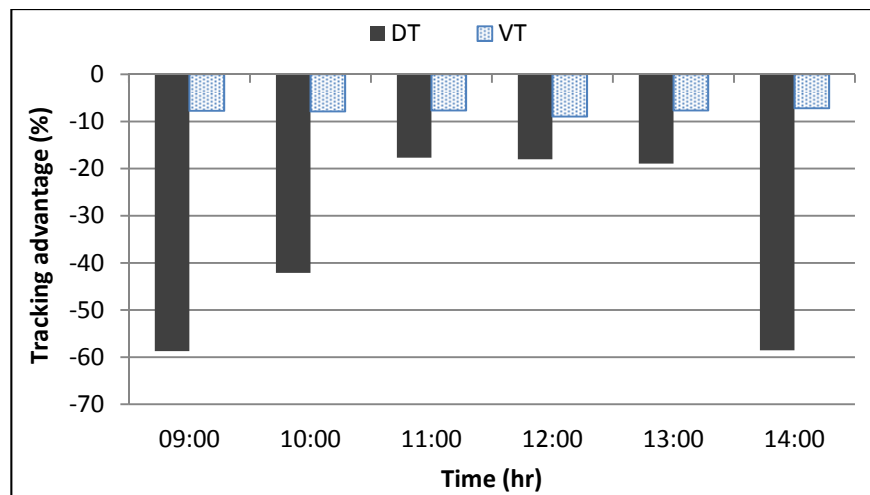


Figure 4.8 Tracking advantage versus the tilted system during a cloudy day in Montreal

4.2.3 Comparison of tracking strategies

In previous sections, one can observe that the dual-axis tracking (DT) strategy is always slightly better than the single-axis one (ST). Figure 4.9 presents this relative advantage of dual-axis tracking and single-axis tracking for each month of the year for all four locations.

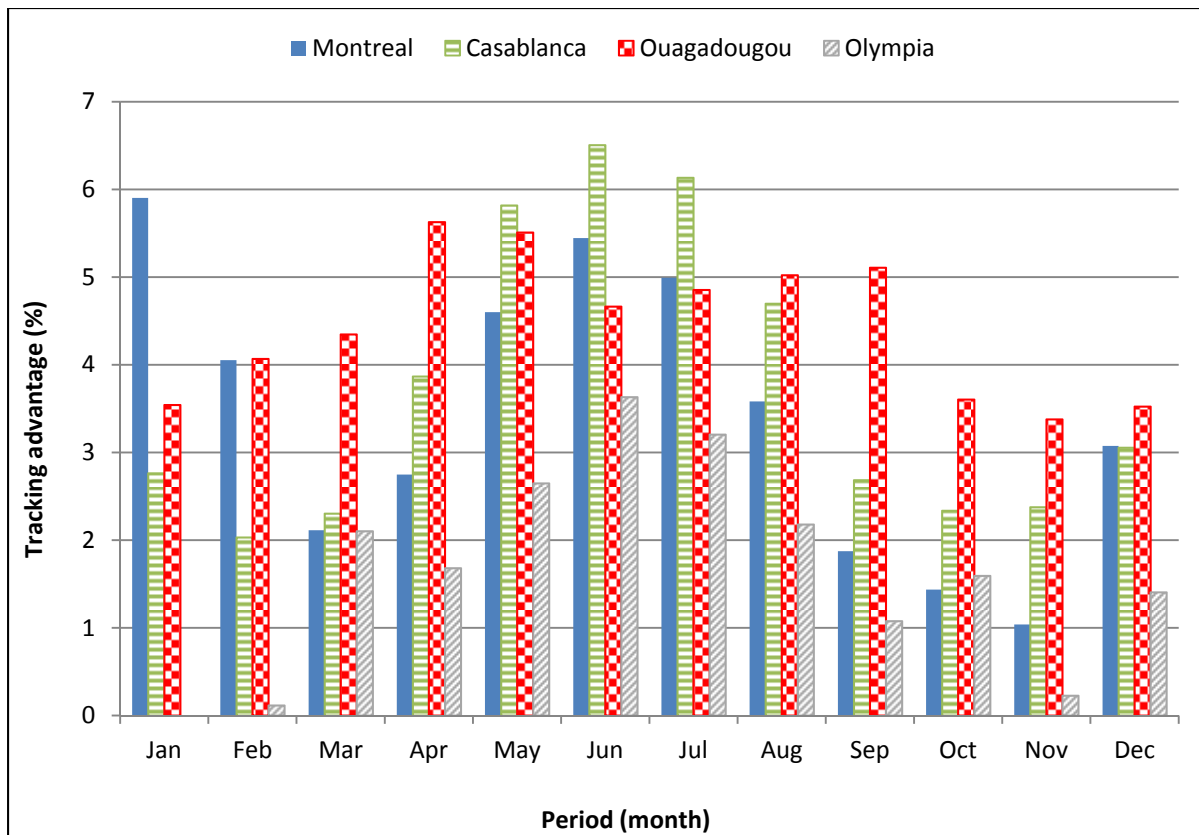


Figure 4.9 Dual-axis tracking advantage versus single-axis tracking for different locations

As it can be seen from Figure 4.9, the dual-axis tracking (DT) systems can produce maximum 6% more electricity compared to the single-axis tracking (ST) systems. In Ouagadougou, the average of DT advantage compared to ST is 4.4%, which is the maximum among other locations. Since the ST system has a larger tilt angle than the DT system, the DT advantage in summer is larger than in other months. In Casablanca, although the average of DT advantage is 3.7% over the year, the advantage could reach to 6.5% in summer. In

Montreal, the DT advantage is insignificant (1-2%) during the months which have many cloudy days (April and November). During the summer the DT advantage is between 4% and 5.5%, because the sun moves through a path near overhead in the sky. The average of DT advantage compared to ST is 3.4% over a year in Montreal. As it mentioned in previous chapters, the single-axis tracking systems are simpler and cheaper than the dual-axis tracking systems. Hence, utilization of a more expensive and more complicated tracker (DT) in a project should be justified according to the advantage of dual-axis tracking.

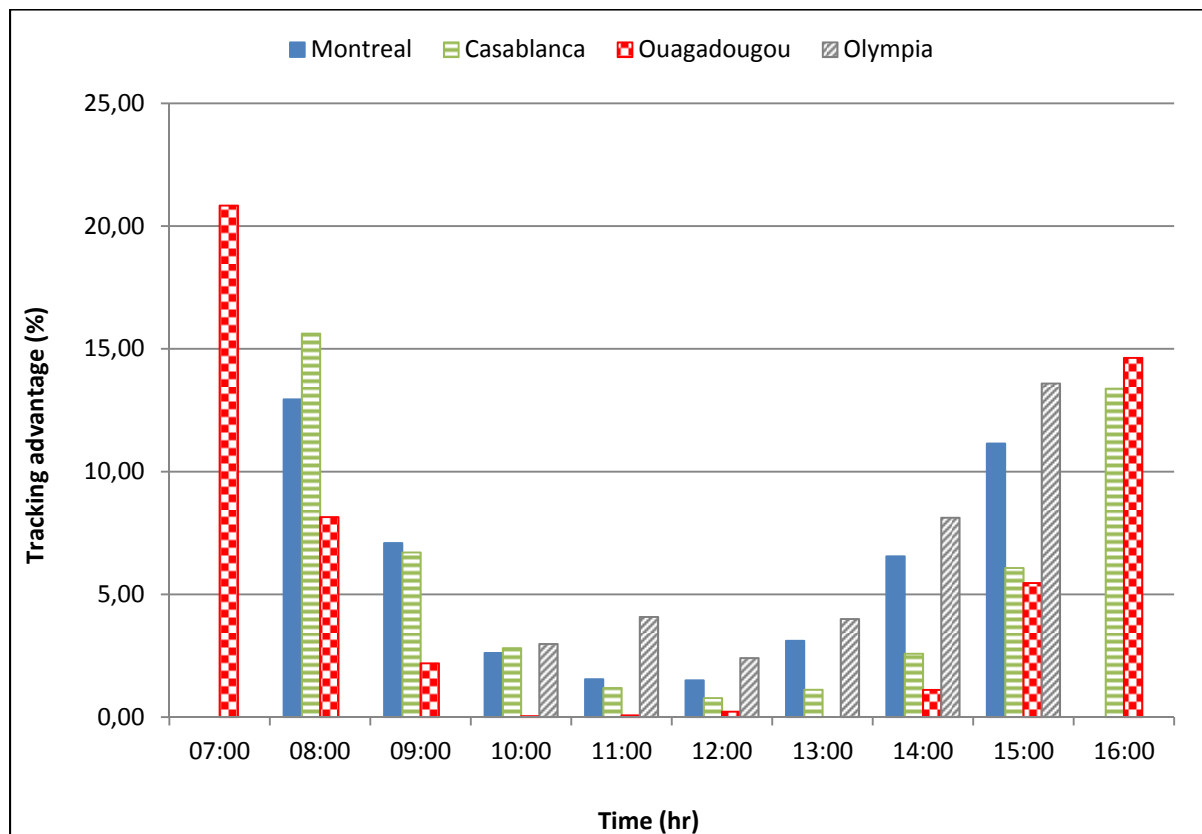


Figure 4.10 DT advantage versus ST advantage during a clear winter day for different locations

Figure 4.10 shows the dual-axis tracking advantage versus the single-axis tracking during a clear winter day for different locations. Here, the advantage variation has a similar trend for all locations. Near the sunset and sunrise the tracking advantage has larger amount compared

to around noon. According to this figure, tracking advantage magnitude depends on the solar radiation intensity. In Ouagadougou, the DT advantage has larger amount compared to other locations.

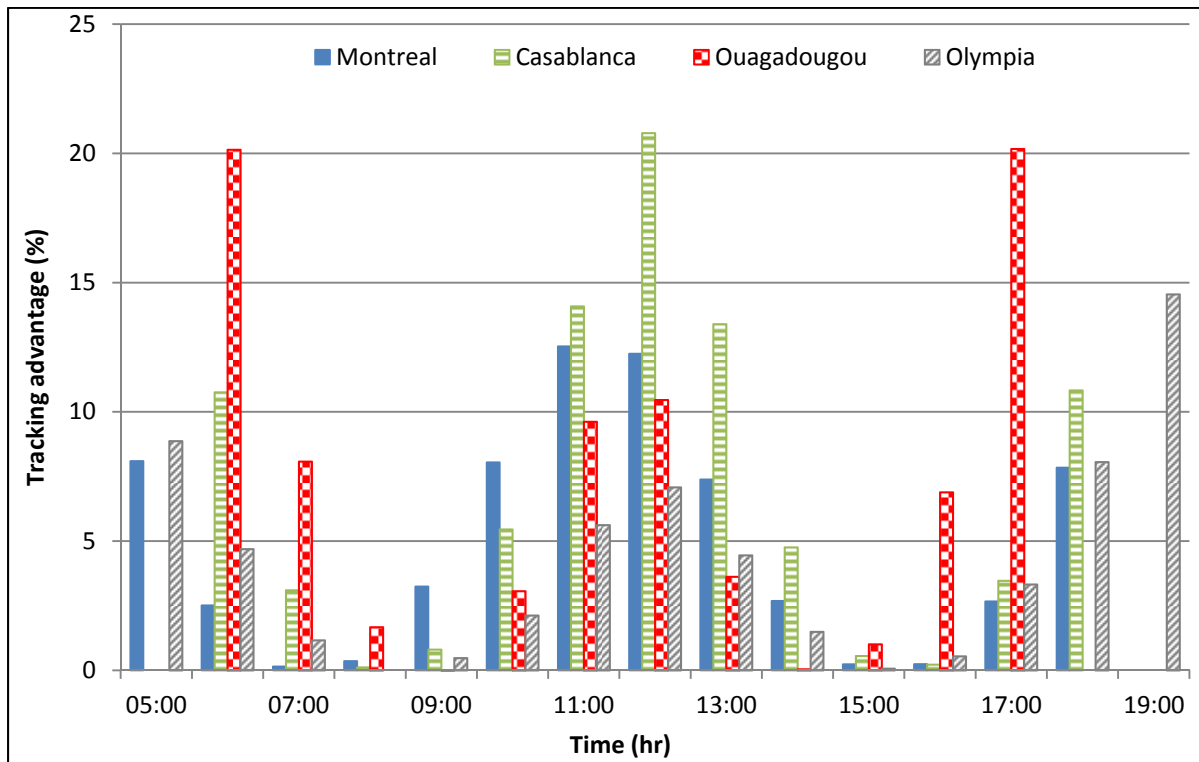


Figure 4.11 DT advantage versus ST during a clear summer day for all locations

Figure 4.11 presents the DT advantage versus ST systems during a clear summer day for all locations. Here again, tracking advantages have similar trend for all locations. Near the sunrise, sunset, and at noon the DT advantage is considerably higher, from 6% in Olympia to 20% in Casablanca and Ouagadougou, than other hours of the day. During a clear summer day, DT advantage average is almost 7% for Casablanca and Ouagadougou, 4.9% for Montreal, and 4.1% for Olympia. Obviously, tracking the sun is more crucial near the sunrise and sunset compared to other hours of the day.

There is no need to present results for an overcast day as it is clear from Figure 4.7 and Figure 4.8 that the dual-axis tracking strategy impairs the results much more than the single-axis tracking one for such conditions.

Results from Figure 4.9 and Figure 4.11, may suggests that a proper seasonal inclination could improve the yield (performance) of the single-axis tracking. Hence, for small producers this could be an incentive to tilt their single-axis tracking systems twice or four times per year manually instead of using the more expensive DT system. Of course, the benefits from this strategy would depend on the size of the farm, cost of energy, reliability of DT systems, etc. This has not been considered herein.

4.2.4 Recommended tracking strategy

According to the all results and comparisons, tracking advantage depends on the amount of solar radiation. In locations with low amounts of radiation (like Olympia), it would be unnecessary to track the sun precisely. On the other hand, in locations with abundant solar radiation, like Ouagadougou, tracking the sun would improve the performance of PV systems significantly. Since the average of DT advantage compared to ST is between 1% and 4.5% over a year, a single-axis tracking system with seasonal tilt adjustments could provide almost the same yield as the dual-axis tracking systems. A very simple mechanical mechanism could be utilized for seasonal tilt adjusting manually.

CONCLUSION

In the Solar Canada 2010 conference, the Canadian Solar Industries Association (CanSIA) published a strategy for the future entitled “Solar Vision 2025”. According to this report, the total installed PV capacity in Canada was 66 MW in 2009 and it could reach between 19 and 25 GW until 2025. Several companies participated in the “Micro feed-in tariff program” section. Sun tracking PV systems was one of the main subjects that companies were interested in. Numerous studies show between 20% and 50% more solar incident solar energy for tracking systems as compared to fixed systems. The performance of PV systems depends not only on their location, but also their orientation. Although they increase the electricity production of PV systems, they also increase the complexity and cost of the project. Canada has severe weather conditions that affect the performance of PV systems. Despite of the importance and popularity of PV systems, there is a lack of knowledge in energetic, economical, and environmental performance of sun tracking PV systems in Canada. This research has tried to improve the energetic part of sun tracking PV systems knowledge.

The main objective of this research was to investigate the performance of sun tracking PV systems operating in Canada and compares it with other locations. Four typical climates have been selected to study various weather and environmental effects on PV systems. All systems have similar components with different orientations (horizontal, inclined, single-axis tracking, and dual-axis tracking). Each system is comprised of polycrystalline modules with total capacity of 14.40 kW.

Detailed theoretical performance analyses were performed for all systems. Results were compared focusing on arrays incident solar energy, electricity production, efficiency, and modules temperature. Analyses have been carried out in annual, monthly, and daily periods. Additionally an optimum tracking strategy for PV systems operating in south Canada was presented.

The dual-axis tracking system provides the best performance and captures the maximum amount of solar radiation. However, the single-axis tracking systems are single axis and therefore much cheaper and simpler than dual-axis trackers. In Montreal, the dual-axis tracking system receives only 3.7% more solar radiation and produces only 3.4% more electricity than the single-axis tracking system.

In Montreal, tracking the sun is more effective than in other investigated locations due to its geographical situation (high latitude) and abundance of direct sun beams (clear days). In Olympia, which is located at the same latitude as Montreal, tracking the sun is less effective due to many cloudy days in a year.

In Montreal, the arrays incident solar energy was 147.358 MWh and 195.818 MWh for inclined and dual-axis tracking system, respectively. Therefore, the dual-axis tracking system captured 33% more solar energy than the inclined system throughout the year. Moreover, the tracking system produces 36% more electricity than the inclined system. Daily analyses show that benefit of tracking in sunny winter days is larger than in sunny summer days due to the height of the sun in the sky. In cloudy conditions, all systems have almost the same performance and the horizontal position is the optimum one. The specific irradiation in cloudy days is almost 15% of the specific irradiation in clear days. Therefore, tracking the sun in overcast conditions is unnecessary. Provision should be made to switch the dual-axis tracking system to the horizontal position in days for which cloudiness is expected to last for several hours. However, care should be taken in moving the panels not to consume more energy with the tracking systems than the gain between the two positions.

In northern climate countries like Canada, with large amount of snowfall in winter, the reflected radiation from the ground covered by snow is not negligible. Reflected radiation from the ground covered by snow causes an increase of 4.1%, 5.6%, and 6.9% in arrays incident solar energy for inclined, single-axis tracking, and dual-axis tracking system throughout the winter, respectively. This could be increased in locations for which snow falls and last before January and melts after the end of March.

Another environmental parameter that affects the performance of PV systems is ambient temperature. The standard temperature (STC) for PV modules is 25°C. The efficiency of PV modules is decreased with increasing temperature. In Montreal, very low ambient temperature thus improves the performance of PV systems during the winter as compared to warmer locations. For instance, the annual efficiency of dual-axis tracking system is 13.9% and 12.3% in Montreal and Ouagadougou, respectively. Modules temperature could reach 60°C in Ouagadougou which reduces of 17% the modules efficiency. During the winter, snow is accumulated on PV modules and decreases their efficiency. However, even if a small part of the module is not covered by snow, it absorbs the solar radiation eventually and produces electricity. Conversion of the solar radiation to electricity releases heat and removes snow from the panels by melting and gravitation. Early in the morning the modules temperature of tracking systems is considerably higher than that of fixed systems, since they are perpendicular to the sun rays. Therefore tracking the sun could facilitate snow melting from the panels.

Consequently, tracking the sun is very effective in clear weather conditions, while it is counterproductive in overcast days. The optimum method of sun tracking is using dual-axis tracker to follow the sun in clear sky conditions and go to horizontal position (towards the zenith) in overcast conditions. These results are supported by previous studies. In partial cloudy conditions, depending on the clearness index and reflected radiation from the ground, tracking the sun could be effective or counterproductive.

RECOMMENDATIONS

Of course, additional work could be done for other climate conditions and other countries. Furthermore, in this study polycrystalline modules have been utilized, other types of PV technologies could be studied.

In chapter 3 the effect of tracking on temperature of PV modules has been studied. Tracking the sun facilitates snow melting from modules. It had been assumed that modules had not been covered by snow and analyses have been done for clear modules. More precise studies considering snow coverage could generate interesting results.

In Ouagadougou, one of the major environmental problems that affect the performance of PV systems is dust. In this work, the effect of dust and air pollution on performance of PV systems has been neglected. Future studies could consider additional scattering by air pollution and dust on PV systems.

In this work clear and overcast days have been discussed, but partially cloudy days also have significant importance for PV systems. The decisions of moving to horizontal position or following the sun depend on clearness index. Future studies could estimate the critical irradiation that determines the moment of changing the tracking method.

Finally, the single-axis tracking system with seasonal variation of tilt angle could be worth more research. Finding the optimum tilt angle for each season and determining the appropriate time for modifying the tilt angle are major challenges for future studies. Moreover, economical results could be interesting for industries and customers, because single-axis tracking systems are simpler and more acceptable for regular customers.

ANNEX I

PERFORMANCE ANALYSIS OF SOLAR TRACKING PHOTOVOLTAIC SYSTEMS OPERATING IN CANADA (SOLAR ENERGY JOURNAL)

Mostafa Mehrtash, Guillermo Quesada, Daniel R. Rousse

Industrial Research Chair in Energy Technologies and Energy Efficiency, École de
Technologie Supérieure, Montréal, Canada H3C 1K3

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Abstract

This paper deals with demonstrating the performance of solar tracking photovoltaic (PV) systems. Solar tracker is a device that improves the incident solar radiation upon PV systems by minimizing the solar irradiance angle. Four different grid connected free-standing PV systems have been designed and analyzed: horizontal, tilted, single-axis tracking, and dual-axis tracking. The performance analysis of the systems focuses on array irradiance, electricity generation and efficiency. An anisotropic sky model has been employed to estimate the hourly incident solar radiation upon these systems. The radiation has been split into direct and diffused radiation according to Reindl's radiation model with reduced correlation. Designed PV systems have been investigated regarding the following scenarios: during the year, for clear and overcast winter days, for clear and overcast summer days. The analyses have been done for climate conditions prevailing in Toronto, Canada. The simulation results show that the dual-axis tracking array provides the best performance over a year. It receives 33% more solar radiation and generates 36% more electricity than the tilted system. On clear winter days, compared to the tilted system, the dual-axis tracking system produces 32% and 29% more electricity in high albedo and low albedo conditions, respectively. During a clear summer day with high solar radiation intensity, the dual-axis tracking and single-axis tracking systems produce 72% and 64% more electricity than the tilted system, respectively.

Albedo effect causes an increase of 3.1%, 5.8%, and 7.9% in electricity production of the tilted, single-axis tracking and dual-axis tracking system respectively, over a winter. The results of this research support the idea that tracking the sun is effective on clear days, and could be counterproductive on overcast days.

A I-1 Introduction

The past decade has seen the rapid advancement of solar technology to fulfill the needs of electricity. The quantity of energy produced by PV systems depends on the solar radiation captured by the modules. Tracking the sun allows the PV panels to capture the maximum solar radiation by minimizing the solar incidence angle. Tracking process can be basically done along two axes: azimuth or horizontal (from sunrise to sunset) and zenith or vertical (depending on the height of the sun). Solar trackers operate by using a mechanical mechanism (passive) or an electrical mechanism (active) (Clifford and Eastwood, 2004; Mehleri, Zervas et al., 2010).

Previous research around the world shows 20% to 50% more solar gain by using solar trackers as compared to fixed systems (Abdallah and Nijmeh, 2004; Al-Mohamad, 2004; Abu-Khader, Badran et al., 2008; Lave and Kleissl, 2011; Lubitz, 2011). Helwa et al. studied four different orientations of PV systems to improve the captured solar radiation: fixed system facing the south and tilted at 40°, vertical-axis tracker, tracker with 6° tilted axis parallel to the north-south direction, and dual-axis tracker. One year measurements of solar radiation and electricity production of these systems shows an increase of 11%, 18%, and 30% in captured radiation by azimuth, north-south, and dual-axis trackers, respectively, over the stationary system. These systems have operated in Germany which is located at 48° latitude (Centre for Energy, 2011).

Salah Abdallah studied four different tracking PV systems operating in Amman, Jordan (latitude of 32°): dual-axis, vertical-axis, east-west, and north-south. These systems have been compared to a fixed system tilted at 32°. The results show 43.9%, 37.5%, 34.4%, and

15.7% more output power for the dual-axis, east-west, vertical-axis, and north-south tracking system, respectively (Abdallah, 2004).

In Northern Algeria (latitude of 36.8°), tracking the sun is very effective during clear days. A dual-axis tracking system produced 25%-53% (proportional to radiation intensity) more electricity than a fixed system tilted at yearly optimum angle (Koussa, Cheknane et al., 2011).

Although dual-axis trackers follow the sun more precisely, they increase the initial cost and complexity of the system. A single-axis tracker is considerably simpler and cheaper than a dual-axis one. Compared with a fixed system tilted at yearly optimum angle in China, a vertical-axis tracking PV system can capture 28% more solar radiation in areas with abundant solar resources and 16% more in areas with inadequate solar resources. In addition, an optimal vertical axis tracker can capture 96% of the annual solar radiation captured by a dual-axis tracker (Li, Liu et al., 2011).

Huang and Sun designed a new single-axis three position tracker having a simple structure and low cost. This tracking method adjusts the panels three times in a day: morning, noon, and afternoon. The proposed method produces 24.5% more output power than a fixed system tilted at latitude angle (25°). Daily experiments show that this tracking method can provide an almost similar performance as a dual-axis tracking system in Taiwan (Huang and Sun, 2007). The long-term experiments show that this tracking system can perform very similarly to the single-axis continuous tracking system (Huang, Ding et al., 2011).

Tomson proposed a daily two-positional tracking method for a high latitude location (Estonia 60°) that is simple and requires minimum energy. The seasonal yield is increased by 10-20% over the yield of a fixed system tilted at an optimum angle (Tomson, 2008).

On the other hand, tracking the sun is not necessary during overcast days. The fixed systems can produce almost the same amount or even 10% more electricity than the tracking systems.

During partially clear days, depending on the clearness index, tracking the sun could be useful or counterproductive (Koussa, Cheknane et al., 2011).

An experimental study (Kelly and Gibson, 2011) at the GM Proving Ground in Milford, USA (latitude of 42°) shows that a tracked PV system captures twice as much solar radiation as a horizontal system on sunny days. However, during cloudy periods, tracking the sun is counterproductive since the main part of the solar radiation is diffused. The authors reported that on cloudy days a horizontal PV system can capture 50% more solar radiation than a tracking system.

Kelly et al. measured the solar irradiance of PV systems during overcast periods. They utilized six sensors to measure the irradiance upon a horizontal (H) and a dual-axis tracking (DT) system which looks directly toward the sun. The following equation was derived to calculate the tracking advantage (TA) of a dual-axis tracking system versus a horizontal system.

$$TA_{DT-H} = \frac{\left(1 - \frac{H}{DT}\right)}{\left(\frac{H}{DT}\right)} \quad (\text{A I-1})$$

In 2010, the Canadian Solar Industries Association (CanSIA) published the eagerly expected strategy for the future entitled “Solar Vision 2025” (Canadian Solar Industries Association, 2010). According to this, the total installed PV capacity in Canada was almost 66 MW in 2009 and it could reach between 9 and 15 GW by 2025. Numerous companies participated actively in the Ontario program section entitled “Micro feed-in tariff”. The conference mainly focused on sun tracking PV systems and their performance in Canada.

However, there is a lack of studies about the performance of PV tracking systems in Canada. Performance of PV systems also depends on local climate conditions and Canada has

particularly severe weather conditions. Several environmental parameters affect the performance of PV systems operating in this geographical position such as very low ambient temperature, frost, ice, and snowfall.

The primary objective of this research is to carry out the performance analysis of sun tracking PV systems operating in Canada. Meanwhile, the advantage of tracking is investigated in monthly and daily periods with the purpose of determining the best and worst conditions for sun tracking.

This study is performed for weather conditions prevailing in Toronto, Canada. Four different configurations of PV systems are presented in this work: horizontal, inclined, single-axis tracking, and dual-axis tracking. The simulations have been carried out with PVSOL Pro 4.5 for daily and monthly periods. PVSOL is a product of Valentin Energy Software Company. This software is able to use either a linear or dynamic temperature model. Performance modeling is available for the following module technologies: c-Si, CdTe, CiS, Ribbon, HIT, and μ c-Si. For weather data, it uses MeteoSyn, Meteonorm, PVGIS, NASA SSE, and SWERA.

This paper is organized as follows. Section AI-2 introduces the fundamentals of incident solar radiation and calculations of solar incidence angles of different surfaces. Section AI-3 explains the designed systems, assumptions, and simulated scenarios. Section AI-4 presents and discusses the results of the simulations. Finally, section AI-5 summarizes the results and presents the conclusions of the study.

A I-2 Fundamentals of solar radiation incident upon PV systems

Here, the fundamentals of incident solar radiation are briefly reviewed. The radiation outside the earth's atmosphere is called extraterrestrial radiation (G_{on}). There are several conflicting reports about the accurate amount of extraterrestrial radiation. Duffie and Beckman present an equation that gives an almost accurate amount of extraterrestrial radiation as a function of

the day number (n) (Duffie and Beckman, 1974). The solar constant (G_{sc}) has been estimated as 1367W/m^2 with an uncertainty in the order of 1%.

$$G_{on} = G_{sc} \cdot \left[1 + 0.033 \cos\left(\frac{360n}{365}\right) \right] \quad (\text{A I-2})$$

Hourly extraterrestrial solar radiation (Wh/m^2) upon a horizontal surface between sunrise and sunset can be represented by

$$I_o = \frac{12 \cdot G_{sc}}{\pi} \cdot \left[1 + 0.033 \cos\left(\frac{360n}{365}\right) \right] \cdot \left[\cos \varphi \cdot \cos \delta \cdot (\sin \omega_2 - \sin \omega_1) + \frac{\pi \cdot (\omega_2 - \omega_1)}{180} \cdot \sin \varphi \cdot \sin \delta \right] \quad (\text{A I-3})$$

φ is the latitude of the location which is equal to $43^\circ 40' \text{N}$ for Toronto and δ is the declination angle that can be derived as

$$\delta = 23.45 \sin\left(2\pi \cdot \left(\frac{284 + n}{365}\right)\right) \quad (\text{A I-4})$$

Solar hour angle (ω) is the 15° per hour of angular displacement of the sun from local meridian with positive value in the afternoon and negative value in the morning. The reference meridian is used to calculate the local standard time. The local standard meridians are located at 15° intervals from the Greenwich meridian (longitude 0°). The LSM for Toronto is 75°W which means that the local time is 5 hours behind Greenwich Time. LST is the local solar time which can be calculated by using the time corrections.

$$\omega = 15 \frac{\text{deg}}{\text{hr}} (LST - 12\text{hr}) \quad (\text{A I-5})$$

Incident hourly solar radiation on each surface consisted of three components: direct (beam) radiation, diffuse radiation, and reflected radiation from the other surfaces seen by this plane, that can be expressed as

$$I_T = I_{T,b} + I_{T,d} + I_{T,refl} \quad (\text{A I-6})$$

The incident solar radiation upon a surface is a function of the tilt angle and azimuth angle. The maximum absorption of solar radiation occurs when the panel surface is perpendicular to the direct sun's rays ($\theta=0$).

Several attempts have been made to calculate the solar radiation on surfaces. Basically, two main types of models have been presented, isotropic sky and anisotropic sky. In isotropic sky models, like Hottel's, it is assumed that all diffuse radiation is uniformly distributed over the sky dome and that reflection on the ground is diffused. Circumsolar and horizon brightening are assumed to be zero (Duffie and Beckman, 1974).

Liu and Jordan (1963) derived the isotropic diffuse model which is more precise. It illustrates that the radiation on a tilted surface is consisted in three components: direct, isotropic diffuse, and reflected from the ground. This model is easy to understand but it also embeds an underestimation. The isotropic sky model assumes that the intensity of diffuse radiation is uniform over the whole sky. Therefore, the incident diffuse solar radiation on a tilted surface depends on the fraction of sky seen by it. To calculate the incident reflected radiation from the ground, the field of view seen by the surface is considered as a diffuse reflector (Loutzenhiser, Manz et al., 2007).

Anisotropic sky models take into account the circumsolar diffuse and/or horizon-brightening components. Hay and Davies (1980) estimated an anisotropic sky model in which diffuse radiation from the sky is composed of an isotropic part and circumsolar part, but horizon brightening is neglected (Noorian, Moradi et al., 2008). Hence, incident solar radiation on each surface can be presented by

$$I_T = I_b \cdot R_b + I_d \cdot R_d + I \cdot R_{refl} \quad (\text{A I-7})$$

Where I_b is the hourly direct solar radiation on a horizontal surface (Wh/m^2), R_b is the geometric factor that is the ratio of direct solar radiation on an inclined surface to the direct solar radiation on a horizontal surface, and “ \cdot ” denotes dot product. The geometric factor can be expressed as

$$R_b = \frac{\cos \theta}{\cos \theta_z} = \frac{\cos(\varphi - \beta) \cdot \cos \delta \cdot \cos \omega + \sin(\varphi - \beta) \cdot \sin \delta}{\cos \varphi \cdot \cos \delta \cdot \cos \omega + \sin \varphi \cdot \sin \delta} \quad (\text{A I-8})$$

R_d is the factor of angle for an inclined surface to the sky at any time that is presented by

$$R_d = \frac{1 + \cos \beta}{2} \quad (\text{A I-9})$$

I is the summation of hourly direct and diffuse radiation on a horizontal surface. R_{refl} is the factor of angle for an inclined surface towards the ground that depends on the ground reflection coefficient (ρ_g)

$$R_{refl} = \rho_g \cdot \left(\frac{1 - \cos \beta}{2} \right) \quad (\text{A I-10})$$

The anisotropic sky model divides the sky into two zones, a zone for part of the sky around the sun (circumsolar area) and one for the remaining portion of the sky. The diffuse solar radiation from the circumsolar area is projected onto the inclined surface in the same manner as direct solar radiation. Therefore, R_d is represented by

$$R_d = \left[(1 - A_i) \cdot \left(\frac{1 + \cos \beta}{2} \right) + A_i \cdot R_b \right] \quad (\text{A I-11})$$

To compare the circumsolar and isotropic radiation the anisotropic index (A_i) is defined by

$$A_i = \frac{I_b}{I_o} \quad (\text{A I-12})$$

θ is the angle of incidence of direct radiation on a surface that can be presented by

$$\begin{aligned} \cos \theta = & \sin \delta \cdot \sin \varphi \cdot \cos \beta - \sin \delta \cdot \cos \varphi \cdot \sin \beta \cdot \cos \gamma + \\ & \cos \delta \cdot \cos \varphi \cdot \cos \beta \cdot \cos \omega + \cos \delta \cdot \sin \beta \cdot \sin \gamma \cdot \sin \omega \end{aligned} \quad (\text{A I-13})$$

For a single vertical axis tracking (azimuth tracking) plane the incidence angle of direct radiation is

$$\cos \theta = \cos \theta_z \cdot \cos \beta + \sin \theta_z \cdot \sin \beta \quad (\text{A I-14})$$

The slope of the plane is fixed, therefore β is constant. The incidence angle of beam radiation of a tilted axis north-south tracking plane which is parallel to the earth's axis and adjusted continuously can be represented by

$$\cos \theta = \cos \delta \quad (\text{A I-15})$$

The slope that varies continuously can be presented by

$$\tan \beta = \frac{\tan \varphi}{\cos \gamma} \quad (\text{AI-16})$$

Incidence angle of direct radiation of a dual-axis solar tracking plane and its tilt angle variation are represented by the following equations:

$$\cos \theta = 1 \quad (\text{A I-17})$$

$$\beta = \theta_z \quad (\text{A I-18})$$

Equations. A I-2 to A I-18 form the set mathematical description involved in PVSOL to produce the estimates of solar radiation on surfaces arbitrarily oriented anywhere on earth.

A I-3 Numerical analysis description

Four different grid connected free-standing PV systems operating under the climate conditions in Toronto have been designed and analyzed. Toronto is located at the latitude of 43° 40' N and longitude of 79° 24' W. Its climate is classified as humid continental with warm summers and cold winters (A, 2012).

Each array consists of 48 Si Polycrystalline 300 W PV modules. They are connected to each other in four series outline and each series consists of 12 modules. The system has four 4.60 kW KACO new energy inverters that convert the DC current from the arrays into AC current compatible with electrical appliances. Each system has a total capacity of 14.40kW and total PV area of 92.1m². The efficiency of PV panels under standard test conditions (STC) is 15.6%. The module's temperature coefficient of power is -0.45%/K.

The performance analysis of the systems focuses on arrays irradiance, electricity generation and efficiency. System efficiency is an essential parameter in demonstrating the systems performance. Efficiency presents the amount of losses involved and how well the system converts solar radiation into electricity. Inefficiencies are attributed to: module mismatch, diodes, wiring and connections, snow cover, air pollution, high operating temperature, and conversion of electricity from DC to AC. This work doesn't consider the air pollution and the trackers electricity consumption.

The first system is fixed in a horizontal position. The inclined system is tilted at the latitude angle which is 43 ° in Toronto. The next system is a single-axis tracking PV system. Modules are adjusted at the tilt angle of 51°, which is the yearly optimum angle for systems operating

in Toronto. The last system is a dual-axis tracking PV system that tracks the sun continuously.

The anisotropic sky model (Hay and Davies, 1980) has been employed to estimate the hourly incident solar radiation upon the PV systems. The radiation has been split into direct and diffuse according to Reindl's radiation model with reduced correlation (Energy information administration, 2011). Furthermore, the reflected radiation from the modules is considered in calculations. The performance of a PV system is computed by incoming radiation, module voltage at STC, and the efficiency characteristic curve.

The described PV systems have been analyzed monthly and daily. Each analysis has been done for a clear and an overcast day in winter and summer. Selected days are near the winter and summer solstices. A clear sky has less than 30% cloud cover, while an overcast sky has a 100% cloud cover.

During the winter in Toronto, significant amounts of snow are accumulated on the ground. Hence, reflected radiation from the ground (albedo effect) could affect the solar irradiance of inclined PV systems in rural areas. In this paper, two typical winters have been simulated: low albedo (0.2) winter and high albedo (0.8) winter. It is assumed that winter is started from January and ended by March.

A I-4 Results and discussion

A I-4.1 Annual analysis

Annual analysis presents the electricity production and efficiency of the systems over a year. Reflected radiation from the ground, covered by snow, affects the amount of arrays irradiance. Basically the albedo factor value is between 0 and 1. Fresh snow has the albedo of 0.8-0.9. We assumed that in January, February, and March the ground is covered by snow with albedo=0.8.

A I-4.1.1 Average winter reflection albedo=0.2

It is assumed that the albedo factor has the constant value of 0.2 during the year which means that the environment has low reflection rate. However, annual analysis shows an increase of array irradiance of 11%, 42%, and 47% for tilted, single-axis tracking, and dual-axis tracking arrays, respectively, as compared to the horizontal one.

The total electricity production of systems as compared to the horizontal array is 14%, 49%, and 54% more for tilted, single-axis tracking, and dual-axis tracking systems, respectively. The array irradiance percentage increase is not equal to the energy production percentage increase since the correlation between irradiance and relative efficiency of the PV systems is not linear.

Dual-axis tracking and single-axis tracking arrays have the highest efficiencies among these systems. The annual efficiencies are 13.1% and 13.4% for horizontal and tilted arrays, respectively, while the single-axis and dual-axis tracking systems have the efficiency of 13.7% and 13.8%, respectively.

Figure A I-1 shows the electricity generation of these systems throughout a year. Dual-axis tracking PV array absorbs more radiation than other arrays but it has almost similar performance as the single-axis tracking system. The electricity generation of the tilted array is considerably higher than that of the horizontal one, except in summer since the sun moves across the sky through a path nearly overhead while the horizontal plane is almost perpendicular to the direct radiation for a longer time. In November and December, we observed the minimum amount of production, while the average of electricity consumption increases in winter. In Figure A I-1, one can clearly observe the performance of cloudy skies in April and November. In April, the results show that despite longer days, the increase of production in March is not as much as that of May over April. Inversely for November which shows a steep decrease while the days in December are shorter.

The equations to find the tracking advantage of a dual-axis tracking system versus the horizontal and tilted systems are derived from equations A I-19 and A I-20, respectively:

$$TA_{DT-H} = \frac{\left(1 - \frac{H}{DT}\right)}{\left(\frac{H}{DT}\right)} \quad (\text{A I-19})$$

$$TA_{DT-T} = \frac{\left(1 - \frac{T}{DT}\right)}{\left(\frac{T}{DT}\right)} \quad (\text{A I-20})$$

The tracking advantage of a single-axis tracking system versus the horizontal and the tilted systems can be represented by

$$TA_{ST-H} = \frac{\left(1 - \frac{H}{ST}\right)}{\left(\frac{H}{ST}\right)} \quad (\text{A I-21})$$

$$TA_{ST-T} = \frac{\left(1 - \frac{T}{ST}\right)}{\left(\frac{T}{ST}\right)} \quad (\text{A I-22})$$

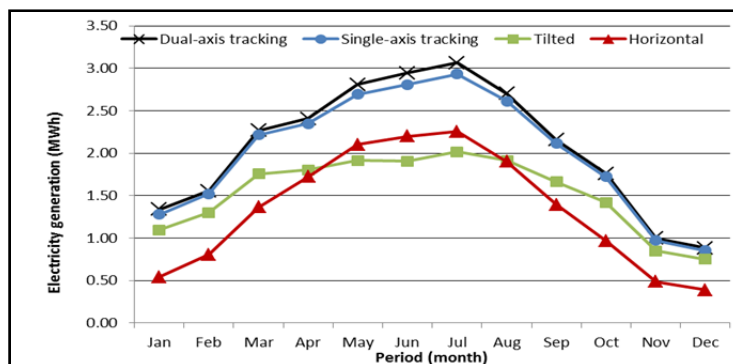


Figure A I-1 Monthly electricity generation (albedo=0.2)

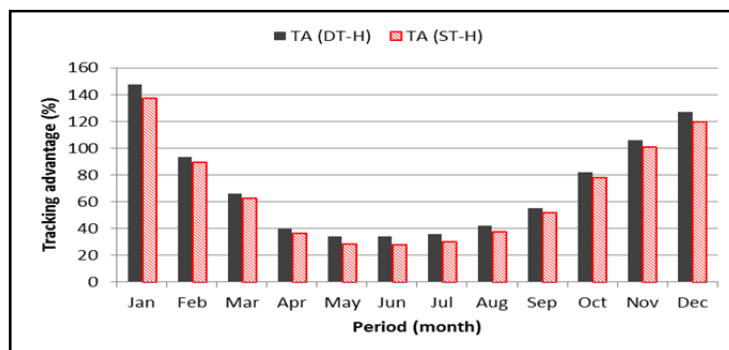


Figure A I-2 Monthly tracking advantage versus the horizontal system (albedo= 0.2)

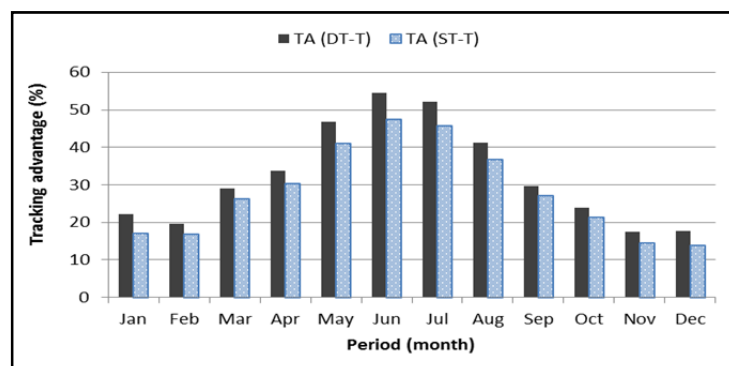


Figure A I-3 Monthly tracking advantage versus the tilted system (albedo= 0.2)

Figure A I-2 and Figure A I-3 show the monthly tracking advantages versus the horizontal and the tilted systems. In Figure A I-2 we observed significantly larger tracking advantages over the horizontal system during the winter. Furthermore, the dual-axis tracking system has a larger tracking advantage over all months. As it can be seen from Figure A I-3, the tracking advantage is superior during the summer when the comparison is carried out with respect to the fixed tilted system. Nevertheless, both figures indicate that there is not much difference between the two tracking strategies, the difference being a couple of percentage points only. The minimum advantage is always superior or nearly 15% for both tracking strategies whether the comparison is against the horizontal or tilted system.

A I-4.1.2 Average winter reflection albedo=0.8

This section provides the results of a year for which the average albedo is 0.8 during the winter. During January, February, and March, when the surrounding environment of arrays is covered by snow, the energy production of the systems is expected to increase, except for the horizontal system, as compared to the low albedo winter. Reflected radiation from the ground covered by snow causes an irradiance increase upon the other three systems. The horizontal array is not sensitive to the change in the environment because it is facing the sky and therefore cannot absorb any reflected radiation from the ground.

Once again, the dual-axis tracking system captured the highest amount of solar radiation, followed gradually by single-axis tracking, tilted and finally the horizontal system.

The monthly electricity production of the systems is shown in Figure A I-4. The electricity production of the systems as compared to the horizontal one is 15%, 51%, and 57% more for tilted, single-axis tracking and dual-axis tracking systems. Certainly, the changes in Figure A I-4 over Figure A I-1 are for the first three months only.

As shown in Figure A I-5, the tracking advantage is almost 30% during the summer, while it reaches 160% in January, an increase of more than 15% over what was obtained for albedo=0.2.

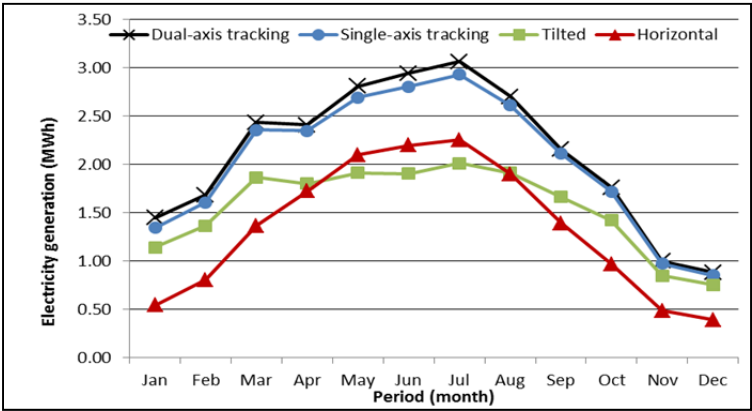


Figure A I-4 Monthly electricity generation (albedo= 0.8)

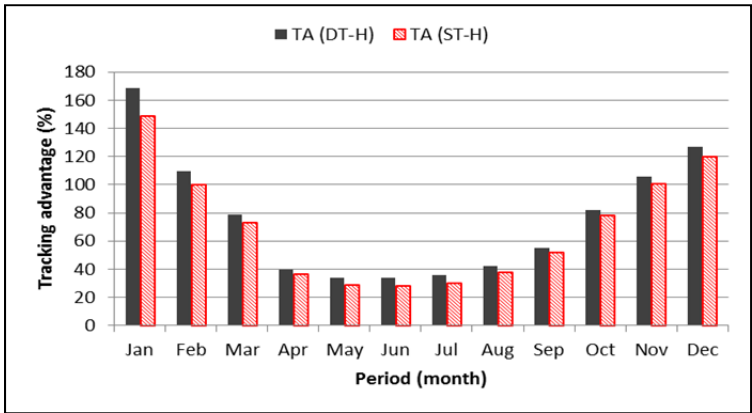


Figure A I-5 Monthly tracking advantage versus the horizontal system (albedo= 0.8)

Figure A I-6 shows the tracking advantages versus the tilted system. During the summer we observed a larger tracking advantage, since the tilt angle of the tilted system is not optimum in the summer. Figure A I-6 shows that there is almost no difference between results for albedo=0.8 and albedo=0.2 when it comes to the comparison of tracking strategies with

respect to tilted systems. One can only observe a slight (1-2%) increase for January, February, and March.

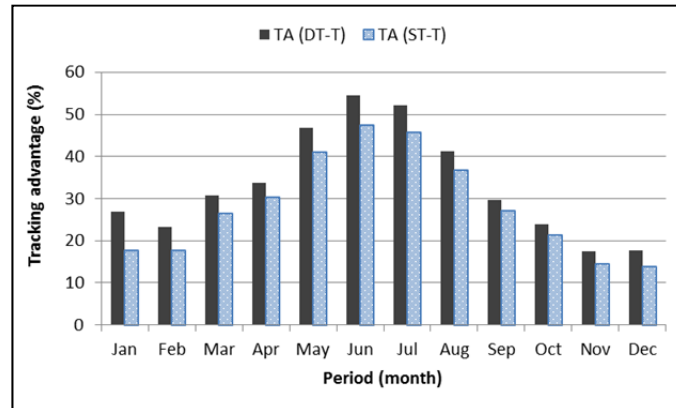


Figure A I-6 Monthly tracking advantage versus the tilted system (albedo= 0.8)

Figure A I-7 shows the electricity generation during two winters, with high and low albedos. The results of these simulations show that reflected radiation from the snow causes an increase of 3.1%, 5.8%, and 7.9% in energy production over the winter for tilted, single-axis tracking, and dual-axis tracking systems, respectively. According to the results obtained from the simulations, the reflected radiation from the ground should improve the performance of PV systems operating in northern climate countries like Canada. It is worth noting that in several regions in Southern Canada, the snowfalls begin in November and that snow coverage may last until the end of April. Thus increasing the trends reported in Figure A I-7.

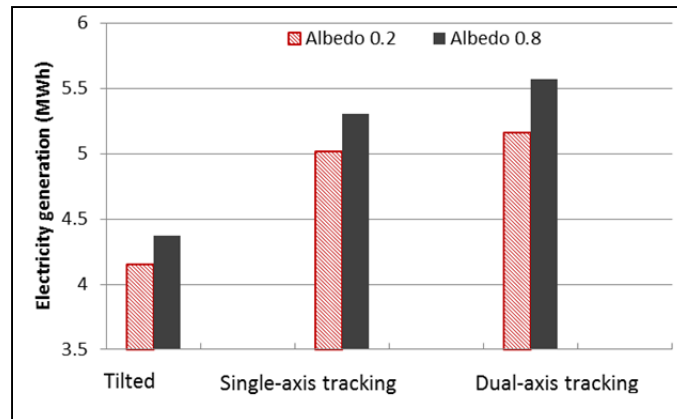


Figure A I-7 Electricity production for the three systems in winter: albedo=0.2, and albedo=0.8

A I-4.2 Daily analysis

This section presents the results obtained from daily simulations for both typical winter and summer days in the vicinity of the solstices.

A I-4.2.1 Winter solstice

PV systems have been studied for clear and overcast days. Winter days have been analyzed with albedo of 0.2 and 0.8.

A I-4.2.1.1 Clear day

During a clear winter day with albedo=0.2, as expected, the dual axis tracker generates more electricity than the others. Daily analysis shows an increase of energy production of up to 145%, 198%, and 218% for inclined, single-axis tracking, and dual-axis tracking arrays, respectively, as compared to the energy produced by the horizontal one (Figure A I-8).

Large increases are reported here as the amount of energy produced by a horizontal collector is very low in latitudes as high as that of Toronto. As Toronto is located in the south of

Canada, Figure A I-8 suggests that horizontal collectors are not the best suited ones for the whole country and thus without regards to the possible accumulation of snow on flat surfaces in winter.

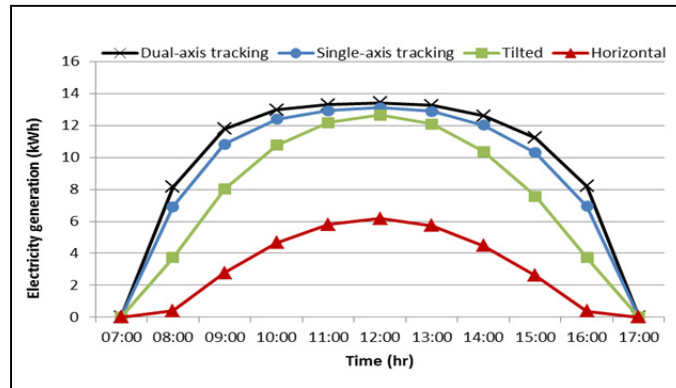


Figure A I-8 Electricity generation during a clear winter day (albedo= 0.2)

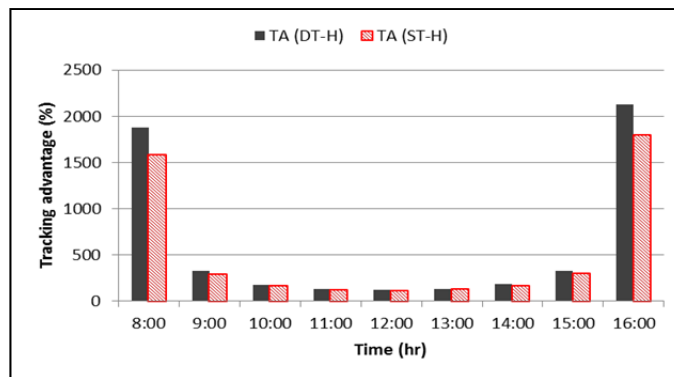


Figure A I-9 Tracking advantage versus the horizontal system during a clear winter day (albedo= 0.2)

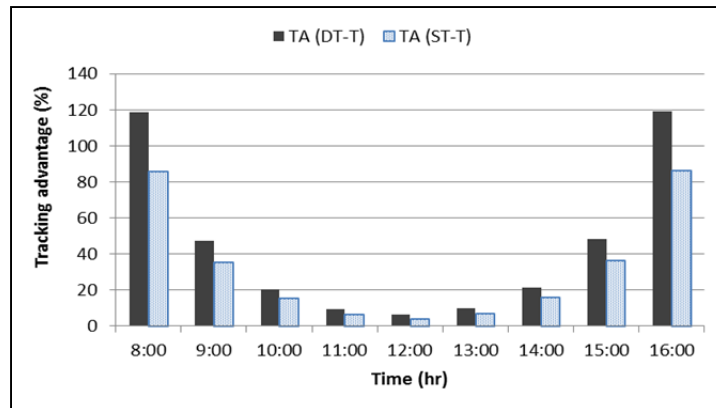


Figure A I-10 Tracking advantage versus the tilted system during a clear winter day (albedo= 0.2)

Figure A I-9 and Figure A I-10 show the tracking advantage of dual-axis and single-axis trackers versus the horizontal and tilted systems, respectively. Near sunrise and sunset, the tracking advantage has a very large value since the fixed systems do not look toward the sun. For the rest of the day the tracking advantage remains above 100% when compared to the horizontal system.

Figure A I-11 shows the electricity production of the systems during a clear winter day with the albedo of 0.8. Comparing Figure A I-8 and Figure A I-11, it can be seen that horizontal system's production has not been affected by the albedo variation. We observed an increase of 3.1%, 3.3%, and 5.2% in electricity production for the tilted, single-axis tracking, and dual-axis tracking systems, respectively, as compared to the clear winter day with albedo of 0.2.

Figure A I-12 compares the averages of tracking advantages over a clear winter day with albedo of 0.2 and 0.8. It is apparent from this figure that increasing the albedo improves the tracking advantage versus the horizontal up to 17%. Meanwhile, we observed a minor increase in tracking advantage versus the tilted.

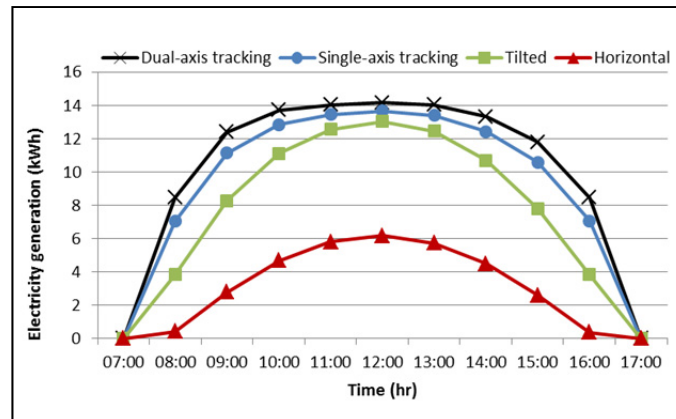


Figure A I-11 Electricity generation during a clear winter day (albedo= 0.8)

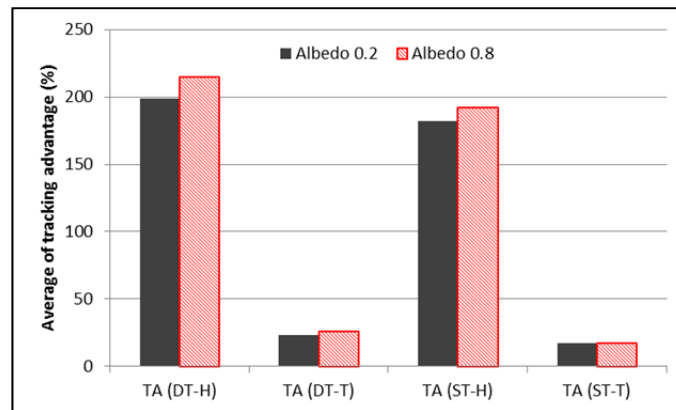


Figure A I-12 Average of tracking advantage in a clear winter day

A I-4.2.1.2 Overcast day

Figure A I-13 shows the electricity production for an overcast day in which the major part of the radiation is diffuse and the albedo is equal to 0.2. The specific irradiance in this overcast day is almost 10% of that of clear days. On an overcast day, the horizontal position is optimum. However, one should note that although this is true for this specific weather condition, the amount of electricity production for each system is very low. The maximum is 2.5 kWh for the horizontal system. Figure A I-14 and Figure A I-15 present the tracking advantages, versus the horizontal and tilted systems, during an overcast winter day. Tracking advantage has negative values during this day, which means that tracking the sun is counterproductive during overcast days.

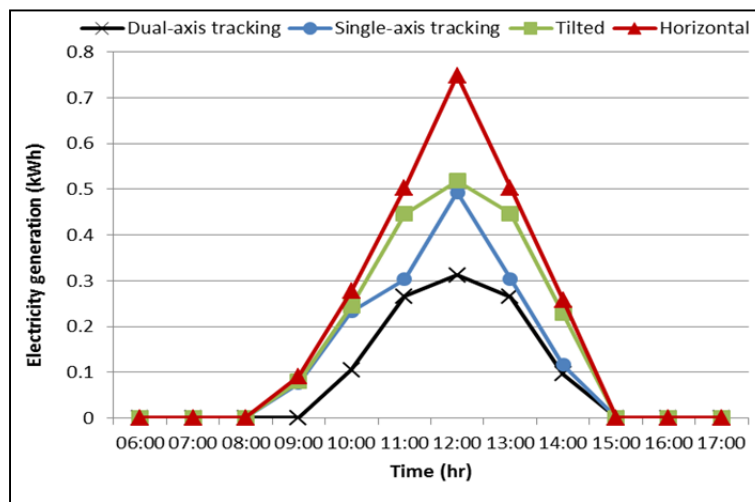


Figure A I-13 Electricity generation during an overcast winter day (albedo= 0.2)

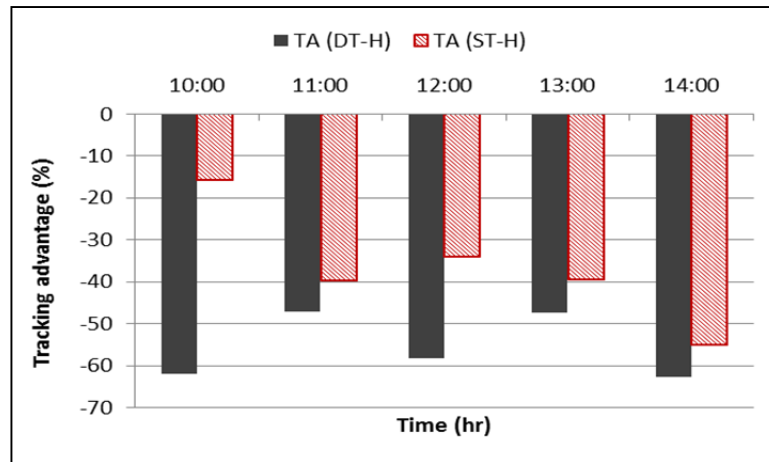


Figure A I-14 Tracking advantage versus the horizontal system during an overcast winter day (albedo=0.2)

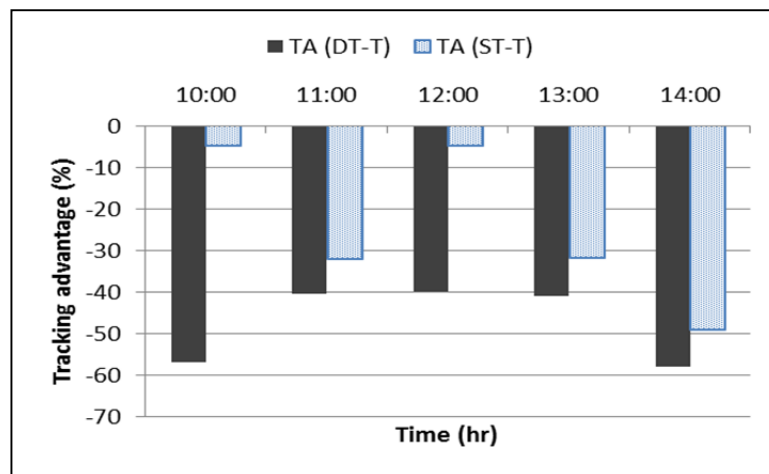


Figure A I-15 Tracking advantage versus the tilted system during an overcast winter day (albedo=0.2)

As shown in Figure A I-16, during an overcast winter day with albedo of 0.8, all the systems have similar performance except the horizontal one. The horizontal system captures more diffuse radiation than others. Here, the reflected radiation deems the performance differences.

Figure A I-17 provides the comparison of tracking advantages during an overcast winter day with albedo of 0.2 and 0.8. The average tracking advantage of dual-axis tracking system versus the horizontal system is -55% when there is no snow. While on a high albedo day the similar advantage is -10%. Single-axis tracking and tilted systems provide almost the same amount of electricity as on a high albedo day. On an overcast day, reflected radiation from the ground covered by snow causes 9%, 39%, and 98% increase in electricity generation of tilted, single-axis tracking, and dual-axis tracking systems, respectively.

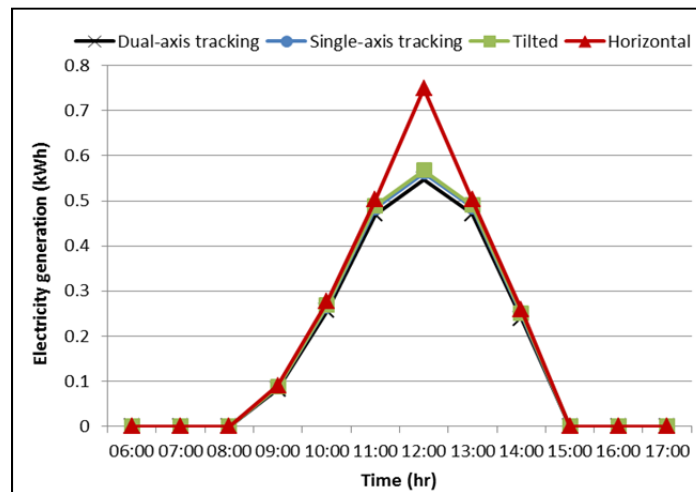


Figure A I-16 Electricity generation during an overcast winter day (albedo= 0.8)

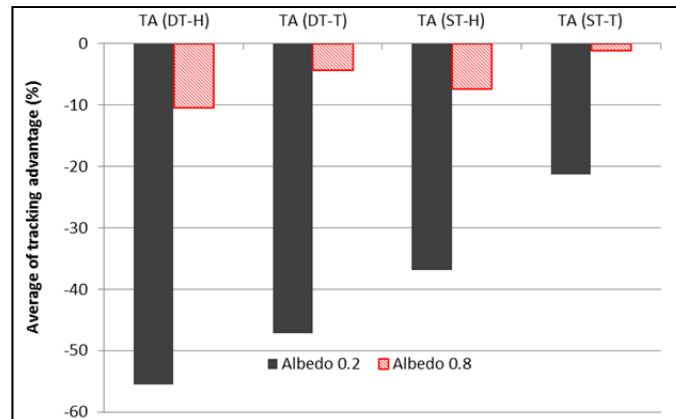


Figure A I-17 Average of tracking advantages over an overcast winter day

Overall the simulations carried out for an overcast winter day near the solstice is showing that the horizontal position should be selected based on its energy increases. This is the opposite of what was observed for a clear day.

A I-4.2.2 Summer solstice

These systems have also been studied on summer days. For summer days the albedo has been assumed to have a constant average value of 0.2.

A I-4.2.2.1 Clear day

A summer day with high intensity of radiation (near the solstice) was selected to analyze these systems. Figure A I-18 shows electricity generation during a clear day in the summer. As for the clear winter day, the dual-axis tracking system produces more energy. The single-axis tracking array has an almost similar performance as the dual-axis tracking array. Nevertheless, at noon, when the sun is overhead in the sky, the single-axis tracking system produces less electricity than other systems, since the solar incidence angle is too large to capture direct radiation. In a clear summer day, the tilted system generates 13% less electricity than the horizontal one. This analysis shows an increase of energy production of up to 42% and 48% for single-axis tracking and dual-axis tracking arrays, respectively, as

compared to the horizontal one. The relative failure of the single-axis tracking system could be compensated by a strategy in which, twice a year, the tilt angle could be modified. Specifically it could be set above 51°in the winters and below this threshold in the summers, to grasp the energy at its peak at noon in the summer time. Certainly, this would be inappropriate for large farms but could be manageable for smaller systems. A similar strategy could be employed for the tracked system: its zenith tilt angle could be modified twice (or more) a year. This has yet to be investigated.

As shown in Figure A I-19 and Figure A I-20, tracking advantages have very small values around noon, while the gains are mostly in the mornings and afternoons.

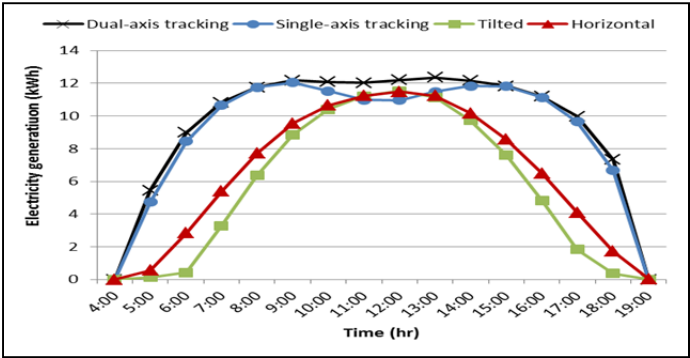


Figure A I-18 Electricity generation in a clear summer day

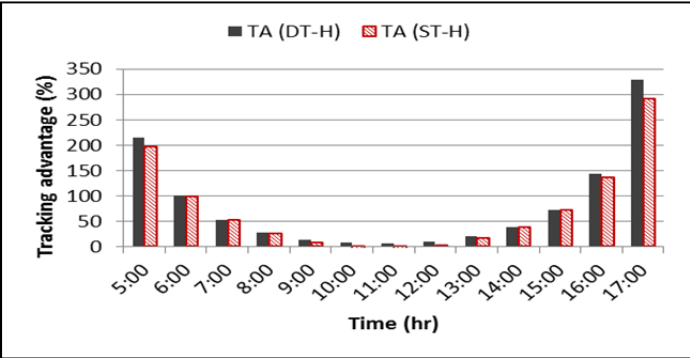


Figure A I-19 Tracking advantage versus the horizontal system during a clear summer day

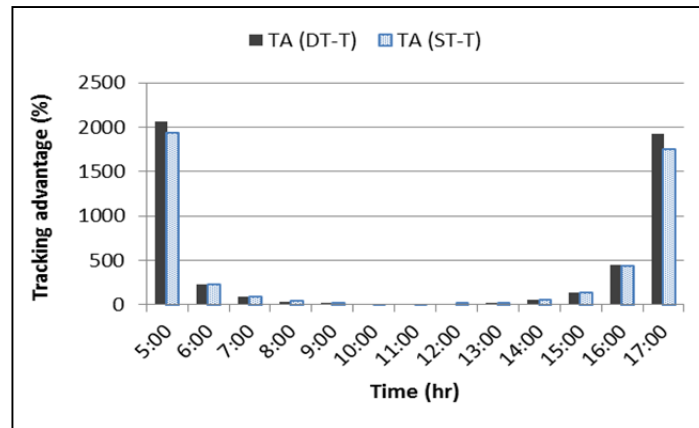


Figure A I-20 Tracking advantage versus the tilted system during a clear summer day

A I-4.2.2.2 Overcast day

As reported in Figure A I-21, during an overcast summer day, while the main part of the radiation is diffuse, all of the systems have almost similar performance and the horizontal one has the optimum performance. As shown in Figure A I-22, tracking advantages compared to the horizontal system has negative value during all that day. Dual-axis tracking system produces the same amount of electricity as the tilted system, while the single-axis tracking system generates 5% less electricity than the tilted system. Overall, the horizontal system produces 14.8% more electricity than the tilted system. Figure A I-23 shows the tracking advantage of tracking systems compared to the tilted system. The tracking advantage average is negative for both the single-axis and dual-axis tracking systems. However, the dual-axis tracking system has positive tracking advantage around noon. It captures more diffused radiation compared to tilted and single-axis tracking systems due to its flatter tilt angle.

Table A I-1 Electricity generation increase percentage as compared to the tilted system

Period	albedo	H	ST	DT
Annual	0.2	-12.3	30.9	35.4
	0.8	-13.4	31.0	36.0
Clear winter day	0.2	-59.2	20.9	29.3
	0.8	-60.0	21.7	32.5
Overcast winter day	0.2	21.4	-22.4	-46.9
	0.8	10.4	-1.1	-4.0
Clear summer day	0.2	16.0	64.4	72.4
Overcast summer day	0.2	14.8	-5.0	-0.02

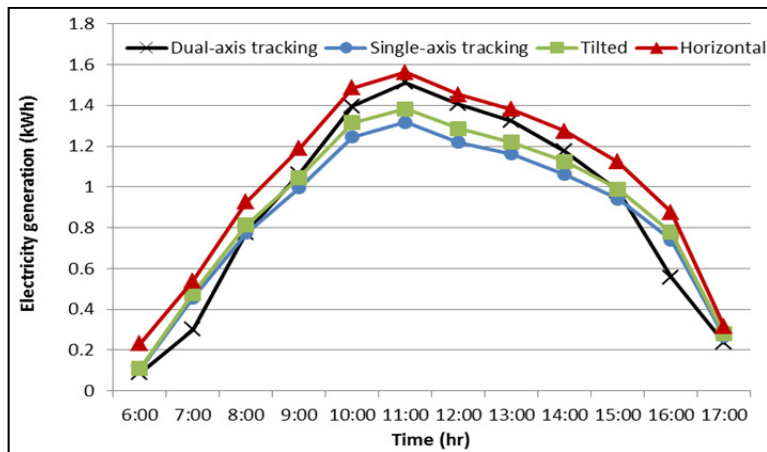


Figure A I-21. Electricity generation during an overcast summer day

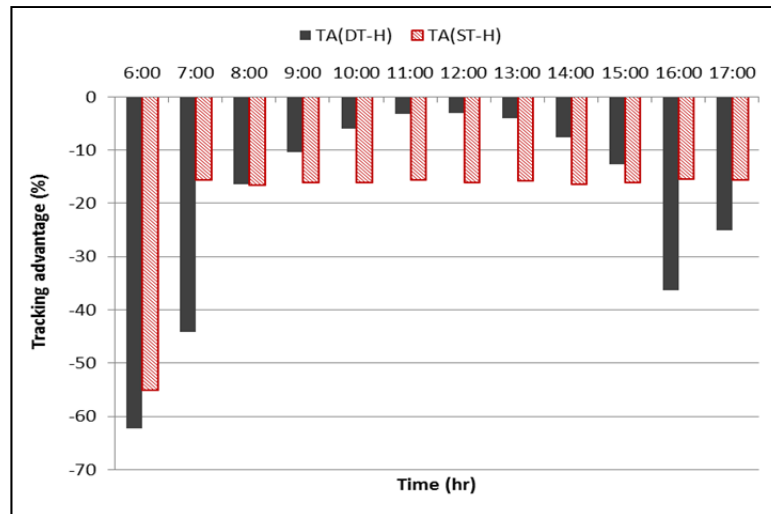


Figure A I-22 Tracking advantage versus the horizontal system during an overcast summer day

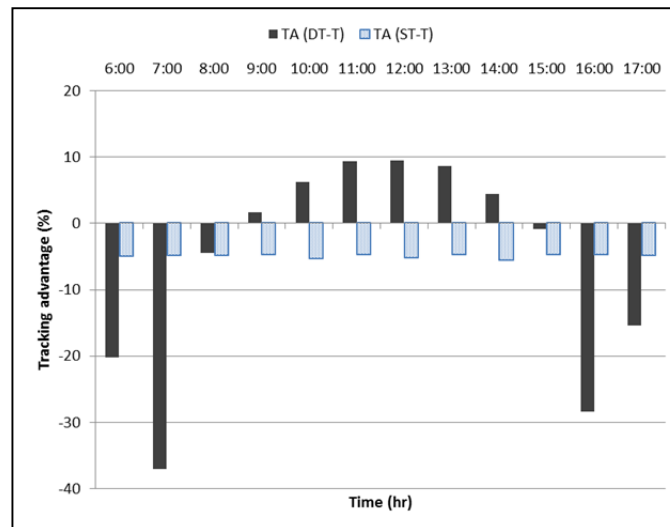


Figure A I-23 Tracking advantage versus the tilted system during an overcast summer day

The results obtained from numerous simulations are summarized in table A I-1. This table shows the increased percentages of electricity production of the systems in different periods as compared to the tilted system. A similar performance of single-axis and dual-axis tracking

systems can be observed, while the single-axis tracker motor consumes less electricity than the dual-axis tracker. Moreover, the horizontal system provides the best performance during both summer and winter overcast days.

A I-5 Conclusion

This paper has evaluated the performance of sun tracking PV systems. Four grid connected free-standing PV arrays were analyzed in daily and monthly periods: horizontal, tilted (at latitude angle), single-axis tracking with yearly optimum tilt angle, and dual-axis tracking. Hourly incident solar radiation upon these systems has been estimated based on an anisotropic sky model, Hay & Davies (1980). The systems performance was computed as a function of arrays irradiance, modules voltage at STC, and an efficiency characteristics curve. Arrays irradiance, electricity production, and tracking advantage have been calculated in different weather conditions.

The simulations results show that the dual-axis tracking array provides the best electricity production performance over a year in Canada. It receives 33% more solar radiation and generates 36% more electricity than the tilted system. Although the dual-axis tracking system may produce 3.8% more electricity than the single-axis tracking system, it is more complicated and more expensive. Furthermore, the consumption of the trackers is proportional to the tracking accuracy (Li, Liu et al., 2011). Then care should be taken when selecting the best tracking strategy with respect to the investment costs and feed-in tariff programs.

On clear winter days, the average tracking advantage of dual-axis tracking versus the tilted system is 32%. Over an overcast winter day, the dual-axis tracking system generates 4% and 13% less electricity compared to the tilted and the horizontal systems, respectively. Hence, tracking the sun on an overcast winter day could be counterproductive. During a clear summer day, the dual-axis tracking and single-axis tracking systems produce 72% and 64% more electricity than the tilted system, respectively. Through an overcast summer day, the tracking advantage is insignificant, which means that all of the systems have almost similar

performances. The horizontal system is the most efficient system, since it has produced 15% and 20% more electricity than the dual-axis tracking and single-axis tracking systems, respectively.

This study has also shown that reflected radiation from the ground covered by snow affects the systems performance considerably. The albedo effect basically improves the performance of tilted and tracking systems. It causes an increase of 3.1%, 5.8%, and 7.9% in electricity production of the tilted, single-axis tracking and dual-axis tracking system respectively, over a winter. Furthermore, on an overcast winter day, we observed 9%, 39%, and 98% increase in electricity production of tilted, single-axis tracking, and dual-axis tracking systems.

The results of this research support the idea that tracking the sun is effective on clear days, and counterproductive on overcast days. Consequently, the optimum method of sun tracking is using the dual-axis tracker to follow the sun during clear sky conditions and then switch to the horizontal position during overcast conditions. These results are supported by previous studies (Chang, 2009; Kelly and Gibson, 2009; Mousazadeh, Keyhani et al., 2009). However, switching to the horizontal position consumes energy, while during the winter the accumulated snow on PV modules significantly reduces the electricity production. Hence, in high albedo conditions, it is recommended to track the sun in clear sky conditions and stay fixed when the sky becomes overcast.

ANNEX II

ÉNERGIE PHOTOVOLTAÏQUE RÉSIDENTIELLE : IMPLANTATION DANS DIVERS PAYS (CIFEM 2012)

Mostafa Mehrtash, Guillermo Quesada, Yvan Dutil, Daniel Rousse

Chaire de recherche industrielle en technologies de l'énergie et en efficacité énergétique,
École de technologie supérieure, Université du Québec, Montréal, Canada H3C 1K3
2^e Colloque International Francophone sur l'Énergétique et la Mécanique, Ouagadougou,
Burkina Faso, Mai 2012

Résumé

Cette étude est réalisée afin de caractériser la performance relative de systèmes photovoltaïques (PV) résidentiels dans trois pays : le Canada, le Maroc et le Burkina Faso. À cette fin, trois systèmes semblables ont été simulés, un à Montréal, un à Casablanca et le dernier à Ouagadougou. Les simulations ont été réalisées par PVSOL Pro pour les jours, les périodes mensuelles et annuelles. Les orientations optimales ont été déterminées. L'analyse sur une base annuelle montre que l'efficacité globale est de 12,5 %, 11,9 % et 11,1 % pour les systèmes situés respectivement à Montréal, Casablanca et Ouagadougou. La réflexion sur la neige et l'effet des températures ambiantes plus basses sur les performances des modules photovoltaïques améliorent les performances du système à Montréal. Enfin, l'utilisation de suiveurs solaires permet d'augmenter d'environ 30 % l'irradiation solaire qui percute le panneau.

Mots clés : énergie solaire, photovoltaïque (PV), effet de la température, suivi solaire.

A II-1 Introduction

Aujourd'hui, l'une des ressources les plus importantes est l'énergie. En raison des ressources limitées en combustibles fossiles, les énergies renouvelables deviennent une alternative intéressante. Parmi toutes les énergies renouvelables, c'est l'énergie solaire qui possède le plus grand potentiel. Ainsi, l'énergie solaire disponible sur la surface de la Terre est 36 PW, alors que les ressources d'énergie éolienne sont de 72 TW, la géothermie 9,7 TW, et l'utilisation de l'énergie humaine est 15 TW (Sick and Erge, 1996; Archer and Jacobson, 2005).

La conversion du rayonnement solaire reçu au sol avec une efficacité de 100 % pourrait théoriquement fournir de l'énergie pour le monde entier en utilisant 1/1000^{ème} de la surface des terres émergées (Ray, 2010). Les systèmes photovoltaïques (PV) constituent une technologie joue un rôle clé en produisant directement de l'électricité à partir du rayonnement solaire, et ce avec un rendement de 10 à 20 % environ. L'énergie solaire photovoltaïque possède de nombreux avantages tels que: absence de pièces mobiles, absence de pollution en fonctionnement, facilité d'adaptation en fonction des caractéristiques d'un site et peu d'entretien. Cette technologie a considérablement progressé au cours des dernières années avec une augmentation de l'efficacité et une baisse importante des coûts de fabrication.

Le rayonnement solaire atteignant une surface comprend des composantes directe, diffuse et réfléchi. La plus grande fraction du rayonnement solaire est directe et prend donc une valeur maximale lorsque les modules sont orientés perpendiculairement à la radiation directe (Ray, 2010). Cependant, les rayonnements diffus et réfléchi (par le ciel et le sol) doivent tout de même être pris en compte lors de l'analyse du fonctionnement des systèmes.

L'emplacement géographique sur la Terre et les conditions météorologiques locales sont d'autres paramètres déterminants du rayonnement solaire. L'angle optimal sur une base annuelle pour absorber la quantité maximale de rayonnement solaire par des modules PV

fixes est égal à la latitude locale aux sites de basse latitude et jusqu'à 14° de moins que la latitude aux hautes latitudes (Lubitz, 2011).

Les suiveurs solaires sont utilisés pour maintenir les capteurs solaires orientés perpendiculairement au Soleil, ce qui permet de capturer plus d'énergie par rapport à un système fixe. Il y a deux principaux types de suiveurs (un ou deux axes), qui opèrent en utilisant soit un mécanisme passif ou actif. Bien que les suiveurs sur deux axes permettent de pointer le Soleil plus précisément, ils augmentent le coût initial et la complexité du système (Mousazadeh, Keyhani et al., 2009).

De nombreux auteurs ont étudié les systèmes de suivi. Salah Abdallah (2004) a conçu, construit et étudié quatre systèmes de suivi pour Amman, Jordanie: deux axes, un axe vertical unique, un seul axe est-ouest et un seul axe nord-sud. La production d'énergie par chaque système est supérieure à celle d'un système fixe incliné à 32° de 43,9 % pour un suivi sur deux axes, 37,5 % pour un suivi est-ouest seulement, 34,4 % pour un suivi selon l'axe vertical seulement et 15,7 % pour un suivi nord-sud. Ce test a été fait en continu pendant une journée claire, le 29 mai 2002. Helwa et al. (2000) ont comparé quatre systèmes photovoltaïques: 1) fixe face au sud et incliné à 40° , 2) suivi sur un axe vertical, 3) suivi sur un axe incliné à 6° en direction nord-sud et 4) un suivi sur deux axes. Sur la base d'une année, la comparaison des résultats montre que l'augmentation annuelle du rayonnement recueilli par les systèmes de suivi azimutal, nord-sud et sur deux axes est de 18 %, 11 % et 30 %, respectivement, par rapport au système fixe. Abou-Khader et al. (2008).

Ont comparé et évalué quatre systèmes: 1) fixe, 2) suivi sur axe vertical, 3) suivi nord-sud, et 4) est-ouest. Des pyranomètres installés sur les panneaux ont mesuré l'irradiation solaire. Les résultats de l'expérience ont montré que le suivi nord-sud était optimal dans ces conditions. Il produisait une puissance de sortie 30-45 % plus élevée que le système fixe incliné à 32° . Koussa et al. (2011) ont mesuré et modélisé des systèmes photovoltaïques avec différents types de suiveurs. Leurs mesures ont eu lieu pendant une période de 18 jours de météo typiques du nord de l'Algérie à une latitude de $36,8^\circ$ (très similaire à celle du Maroc). Le rayonnement direct horaire, le rayonnement global horizontal, le rayonnement diffus et la

température ont été mesurés. La production d'électricité pour chaque système - qui dépend de la consommation d'électricité du suiveur, de l'état du ciel, et de la longueur du jour - a été évaluée. Les résultats obtenus montrent que pendant les jours clairs, le suivi du Soleil est très utile, alors que lors des jours nuageux, il est inutile. Cependant, pendant les jours partiellement nuageux, son utilité est variable en fonction des conditions météorologiques.

Il est à noter que la température a aussi un impact considérable sur les performances de cellules photovoltaïques. Skoplaki et al. (2009) a présenté une étude des corrélations entre l'efficacité et la température. Tant l'efficacité que la puissance de sortie d'un module PV dépendent linéairement de la température de fonctionnement. Il faut donc en tenir compte dans les analyses de rendement.

A II-2 Description des systèmes

Trois systèmes similaires ont été conçus et analysés dans trois pays de l'hémisphère nord avec des climats très différents. Chaque système est composé de 48 modules PV de 300 W pour une puissance totale théorique de 14,4 kW et de 11 kW (net) et quatre onduleurs de 4,4 kW servant à convertir le courant continu en courant alternatif. Ces systèmes sont installés sur des maisons à toitures inclinées.

Christensen et Barker (2001) ont défini un paramètre (w) comme la différence de latitude et de l'angle d'inclinaison optimale pour panneaux photovoltaïques. Ils ont constaté que w variait de 0° à 16° , avec des valeurs plus élevées dans les latitudes élevées et dans les sites avec un indice annuel de clarté moyenne inférieur (Yang and Lu, 2007). Les angles d'inclinaison des panneaux pour chaque site sont choisis en conséquence.

Chaque site présente ses caractéristiques climatiques propres qui affectent les performances du système photovoltaïque. Par exemple, à Montréal, les basses températures hivernales et les chutes de neige améliorent les performances des systèmes PV. À l'opposé à Ouagadougou, les hautes températures et la présence de poussières dégradent les performances.

A II-2.1 Système de Montréal

Le premier système est situé à Montréal, Canada (latitude 45°30'N). Le climat montréalais est de type continental humide, présente de grandes variations de température et reçoit 226 cm de neige par an. L'été, la température maximale quotidienne moyenne est de 26 °C alors que la température minimale quotidienne moyenne de 16 °C. Lors de l'hiver, la température maximale quotidienne moyenne est de -5 °C et la température minimale moyenne est de -13 °C (National Climate Data, 2012). Dans le contexte montréalais, un angle de 45° est optimal pour le système PV. Cet angle a été calculé à l'aide du logiciel PVSOL Pro. (Klise, 2009).

A II-2.2 Système de Casablanca

Le second système est situé à Casablanca, Maroc (latitude 33°36'N). Casablanca bénéficie d'un climat méditerranéen affecté par les courants froids de l'Atlantique. Les fluctuations de température y sont faibles, avec une moyenne annuelle pour le maximum journalier est de 21,2 °C et de 13,6 °C pour le minimum (World Weather Information Office, 2011). Ce système PV est incliné à 30°, qui est l'angle optimum pour cet endroit.

A II-2.3 Système de Ouagadougou

Le dernier système est situé dans la capitale du Burkina Faso, Ouagadougou (latitude 12°20'N). Ouagadougou possède un climat chaud avec 900 mm de pluies par an. La température moyenne maximale quotidienne 35,4 °C et la température minimale quotidienne 22,1 °C (Wikipedia, 2011). L'angle d'inclinaison optimal y est de 15°.

A II-3 Simulation

Les simulations ont été réalisées avec le logiciel PVSOL Pro. À la base, ce logiciel utilise un modèle de ciel isotropique pour le ciel et près du Soleil, mais qui néglige l'augmentation de

la brillance près de l'horizon (Duffie and Beckman, 1974). Les systèmes PV ont été analysés sur une base quotidienne, mensuelle ou annuelle.

La Figure A II-1 montre l'irradiation cumulée (en MWh) sur les panneaux pour chaque mois pendant une période de un an. On constate, sans surprise, que c'est à Ouagadougou que l'irradiation solaire est maximale. En hiver (novembre, décembre et janvier), l'irradiation est minimale à Montréal et à Casablanca, alors que la consommation d'électricité est maximale. En revanche, l'irradiation à Ouagadougou est maximale pendant ces mois, tandis que la consommation d'électricité est faible, en raison des températures plus basses, car elle suit la charge de climatisation.

Cependant, à Montréal, la production augmente rapidement de novembre à mars, car le rayonnement réfléchi par le sol augmente. En effet, le plus souvent le sol est couvert par la neige de décembre à avril. En effet, cette dernière présente un albédo de 0,8 à 0,9 tandis que pour une surface recouverte par de l'asphalte il est de 0,04 à 0,12 et de 0,25 pour une surface d'herbe verte (McEvoy, Markvart et al., 2003).

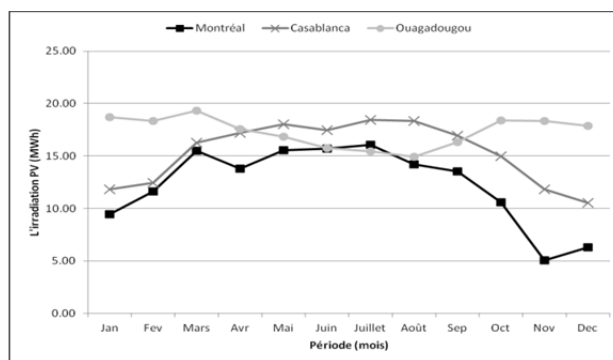


Figure A II-1 Variation annuelle de l'irradiation solaire cumulée sur les systèmes PV en fonction du mois

La Figure A II-2 montre la quantité d'électricité produite (en MWh) chaque année par ces systèmes. Le calcul de cette énergie tient compte de tous les paramètres d'opération notamment de la température de fonctionnement du panneau solaire. Les systèmes marocain

et burkinabé produisent 18,8 % et 24,9 % plus d'électricité que le système montréalais. Cependant, l'irradiation solaire y est de 25,6 % supérieure à Casablanca et de 41,6 % à Ouagadougou (voir tableau A II-1). La différence s'explique par la basse température ambiante à Montréal qui entraîne une augmentation de la production d'électricité du système. En effet, la température annuelle moyenne est de 7,4 °C à Montréal, de 18,4 °C à Casablanca et de 29 °C à Ouagadougou. Alors que la moyenne de la température du module à Montréal est de 16,2 °C, à Casablanca de 29,2 °C et à Ouagadougou elle est de 35 °C.

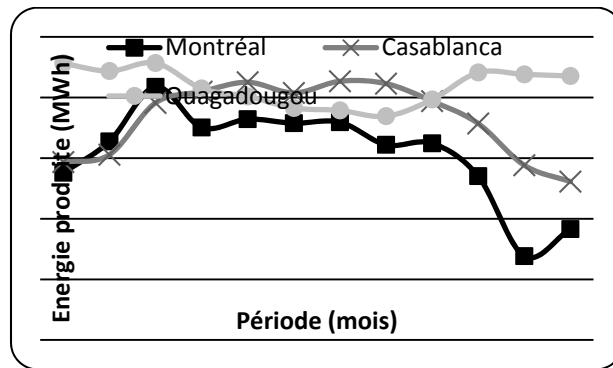


Figure A II-2 Variation annuelle de la production d'électricité des systèmes PV en fonction du mois

L'équation A II-1 montre la relation entre le rendement électrique du module à la température de fonctionnement, η_C , et le rendement électrique du module à la température de référence, $\eta_{T_{ref}}$ (Skoplaki and Palyvos, 2009).

$$\eta_C = \eta_{T_{ref}} [1 - \beta_{ref}(T_C - T_{ref}) + \gamma \log_{10} G_T] \quad (\text{A II-1})$$

où β_{ref} est le coefficient de température et γ est le coefficient de rayonnement solaire. À $T_{ref}=25\text{ °C}$, β_{ref} et γ sont respectivement égaux à $0,004\text{ K}^{-1}$ et 0,12 pour le silicium monocristalin. Le terme $\gamma \log_{10} G_T$ est généralement négligé et considéré comme nul. Ainsi, chaque degré d'augmentation de la température entraîne approximativement une réduction de 0,5 % de pic de puissance de sortie d'un système photovoltaïque (Brinkworth and Sandberg, 2006).

A II-4 Discussion

Le système montréalais est le plus efficace en raison des températures ambiantes plus faibles. Il est à noter qu'en pratique, le système installé à Ouagadougou aurait une efficacité encore plus faible que 11,1 % car le modèle ne tient pas compte de la présence importante de poussière dans l'air qui masque le Soleil en partie et qui se dépose sur les surfaces.

Ces systèmes sont installés sur les toits en pente et ils ne bénéficient pas d'une ventilation naturelle sur leur face arrière. L'ajout d'un tel système améliorerait leur performance, comme le montre le tableau 2. Les systèmes autoportants sont les systèmes les plus efficaces en raison du taux de transfert de chaleur par convection important des deux côtés des modules PV, ce qui limite l'augmentation de température.

Tableau A II-1. Comparaison sur une année

Système	Irradiation annuelle (MWh)	Production d'énergie annuelle (MWh)	Efficacité (%)
Montréal	146,8	18,5	12,5
Casablanca	184,4	21,9	11,9
Ouagadougou	207,9	23,1	11,1

Tableau A II-2. Efficacité avec des systèmes de ventilation

Système	Efficacité (%) avec ventilation naturelle	Efficacité (%) autoportant
Montréal	13,3	13,6
Casablanca	12,4	12,8
Ouagadougou	11,6	12,1

La situation est légèrement différente dans le cas d'un système PV qui suit le Soleil (voir Figure A II-3). Les suiveurs causent près de 30 % d'augmentation de l'irradiation sur les

panneaux pour les deux systèmes ainsi qu'une amélioration sensible de l'efficacité (Tableau A II-3).

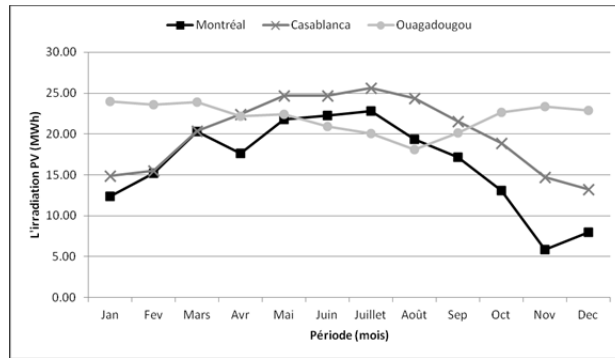


Figure A II-3 Irradiation annuelle avec des suiveurs

Le suivi solaire présente un avantage supplémentaire dans des conditions météorologiques sévères de Montréal. Ainsi, au cours d'une nuit d'hiver de grandes quantités de neige peuvent s'accumuler sur les modules photovoltaïques. D'une part, le panneau solaire peut être placé à la verticale pour faire tomber la neige. Cependant, si cette dernière reste tout de même collée à la surface des panneaux, le suivi présente un autre avantage. En effet, les panneaux solaires s'échauffent sous l'effet du rayonnement solaire et des pertes par effet Joule dues à la production d'électricité. La plus grande perpendicularité des panneaux amplifie ces deux effets. Ainsi, la température de surface du panneau guidé est supérieure de 8 °C à celle du panneau fixe une heure après le lever du Soleil, l'écart se maintenant au cours de la journée. La fonte de la glace en sera d'autant plus rapide. La Figure A II-4 montre la température ambiante et des modules photovoltaïques pour un système guidé ou fixe à Montréal.

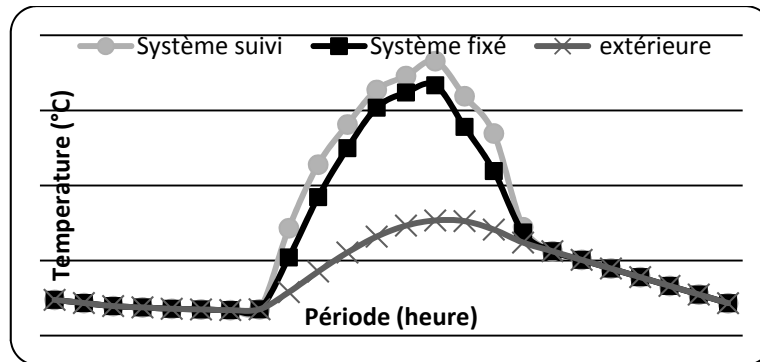


Figure A II-4 Température ambiante et des panneaux solaires à Montréal pour une journée hivernale par temps avec ou sans suiveur.

A II-5 Perspective économique

Un premier estimé de la viabilité économique pour Montréal peut être effectué à l'aide de paramètres simples. Le coût de l'électricité au tarif domestique au Québec est 0,0751\$/kWh après les 30 premiers kWh. De plus, au tarif domestique, on ne paie pas pour l'appel de puissance maximal et il n'existe pas de tarif préférentiel en fonction de l'heure du jour. La production du système de Montréal représente donc une somme hors taxe de 1390 \$ quel que soit le profil de consommation.

Pour obtenir une viabilité économique basée sur une période de retour sur investissement simple (PRIS ou en anglais ROI) de 5 ans, il faudrait que le système – matériel, installation et entretien compris – coûte (hors taxe) environ 7000 \$. Un système de 14 400 W (théorique) à 0,5 \$/W coûterait environ cette somme. Or, le coût nominal des systèmes PV résidentiels de petite taille dépasse actuellement 5 \$/W ce qui indique que beaucoup de recherche est encore requise pour rendre économiquement viable cette technologie dans le contexte économique québécois.

Une discussion à cet effet sera intéressante à tenir lors du congrès pour comparer les situations dans chaque pays.

A II-6 Conclusion

Dans cette étude de trois systèmes PV situés à Montréal, Casablanca, et à Ouagadougou ont été analysés à l'aide du logiciel PVSOL Pro. Les résultats des simulations montrent que bien que le potentiel photovoltaïque à Montréal soit inférieur à deux autres villes, les systèmes photovoltaïques fonctionnent plus efficacement à Montréal, ce qui compense en partie ce déficit. En effet, en hiver, le rayonnement réfléchi par le sol et les faibles températures ambiantes amènent une augmentation significative de la production d'électricité des systèmes photovoltaïques à Montréal.

Tableau A II-3. Performances annuelles avec suivi solaire

Système	Irradiation annuelle (MWh)	Production d'énergie (MWh)	Efficacité(%)
Montréal	195,8	27,2	13,9
Casablanca	240,9	31,5	13,1
Ouagadougou	264,2	32,6	12,3

On note aussi que la mise en œuvre d'un système de ventilation pour les modules qui sont installés sur les toits augmente de 1% de l'efficacité des systèmes. À l'opposé, la température ambiante élevée et de la poussière dans l'air provoquent une diminution de l'efficacité des modules photovoltaïques à Ouagadougou.

De plus, l'utilisation de suiveurs sur deux axes pour ces systèmes a été analysée. Les suiveurs entraînent une augmentation annuelle de l'irradiation solaire de 30 % environ par rapport aux systèmes fixes. En revanche, les traqueurs consomment de l'énergie pour suivre le soleil, augmentent le coût initial et d'entretien, et rendent le système plus complexe. Il resterait donc à pouvoir intégrer ces paramètres à l'analyse afin de voir si au final ce choix s'avère rentable. Cependant, le gain en performance apporté par le système de guidage se fait au prix d'une augmentation de la complexité et des coûts initiaux du système. De plus, l'ajout de moteurs augmente les possibilités de défaillance mécanique, alors que l'absence de composante

mobile est considérée comme un avantage des systèmes solaires. Finalement, l'installation de système de suivi demande plus d'espace, car les panneaux solaires doivent pouvoir se déplacer sans interférer les uns avec les autres.

Enfin, une analyse technico-économique simple a permis de démontrer que pour le Québec, le choix d'installer de tels capteurs ne relève pas de considérations économiques mais plutôt de considérations techniques. En ce sens, en 2012, seuls les endroits dépourvus de connexion au réseau électrique pourraient envisager cette solution de production électrique résidentielle décentralisée.

Remerciements

Les auteurs désirent remercier les partenaires de la Chaire de recherche t3e qui s'investissent dans la réalisation de leurs projets. Des remerciements particuliers ont adressés à Dycosolar. Daniel Rousse est reconnaissant au CRSNG pour une subvention à la Découverte et aux partenaires financiers de t3e.

ANNEX III

COMPARAISON D'UN SYSTÈME PHOTOVOLTAÏQUE RÉSIDENTIEL AU QUÉBEC ET AU MAROC (AMT 2012)

Mostafa Mehrtash¹, Guillermo Quesada, Yvan Dutil, Daniel Rousse

¹ Chaire de recherche industrielle en technologies de l'énergie et en efficacité énergétique, École de technologie supérieure, Université du Québec, Montréal, Canada H3C 1K3

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Résumé

Cette étude est réalisée afin de caractériser la performance relative de systèmes photovoltaïques (PV) résidentiels installés au Canada et au Maroc. À cette fin, deux systèmes semblables ont été simulés, l'un à Montréal et l'autre à Casablanca. Les simulations ont été réalisées par PVSOL Pro pour les jours, les périodes mensuelles et annuelles. Les orientations optimales ont été déterminées. L'analyse sur une base annuelle montre que l'efficacité globale est respectivement de 12,2 % et 11,7 % pour les systèmes situés à Montréal et à Casablanca. La réflexion sur la neige et l'effet des températures ambiantes moins élevées améliorent les performances du système situé à Montréal. Enfin, l'utilisation de suiveurs solaire est discutée.

Mots clés : énergie solaire, photovoltaïque (PV), effet de la température, suivi solaire.

A III-1 Introduction

Aujourd'hui, une des ressources les plus importantes est l'énergie. En raison des ressources limitées en combustibles fossiles, les énergies renouvelables deviennent une alternative intéressante. Parmi toutes les énergies renouvelables, c'est l'énergie solaire qui a le plus

grand potentiel. Ainsi, la puissance solaire disponible sur la surface de la Terre est 36 PW, alors que les puissances relatives des ressources d'énergie éolienne sont de 72 TW, celle de la géothermie de 9,7 TW, et l'utilisation de l'énergie humaine est de 15 TW (Sick and Erge, 1996; Archer and Jacobson, 2005).

La conversion du rayonnement solaire reçu au sol avec une efficacité de 100 % pourrait fournir de l'énergie pour le monde entier en utilisant 1/1000^{ème} de la surface des terres émergées (Ray, 2010). Parmi les différentes techniques de captation de l'énergie solaire, le système photovoltaïque (PV) – qui convertit le rayonnement en électricité – est une technologie dont le rendement oscille entre 10 et 20 % pour des applications commerciales, industrielles institutionnelles et résidentielles (des cellules expérimentales atteignent un taux de conversion de près de 40 %). Cette technologie a considérablement progressé au cours des dernières années avec une augmentation de l'efficacité et une baisse importante de ses coûts de fabrication. L'énergie solaire possède de surcroît de nombreux avantages tels que: absence de pièces mobiles, pas de pollution en fonctionnement, facilité d'adaptation en fonction des caractéristiques d'un site et peu d'entretien.

Le rayonnement solaire atteignant une surface comprend des composantes directes, diffuses et réfléchies. La plus grande fraction du rayonnement solaire est directe et prend donc une valeur maximale lorsque les modules sont perpendiculaires à l'irradiation directe (Duffie and Beckman, 1974). Cependant, les rayonnements diffus et réfléchis (par le ciel et le sol) doivent tout de même être pris en compte pour l'analyse du fonctionnement des systèmes.

L'emplacement sur la Terre et les conditions météorologiques locales sont d'autres paramètres déterminant du rayonnement solaire. L'angle optimal sur une base annuelle pour absorber la quantité maximale de rayonnement solaire par des modules PV fixes est égal à la latitude locale aux sites de basse latitude et jusqu'à 14° de moins que la latitude aux hautes latitudes (Lubitz, 2011).

Les suiveurs solaires sont utilisés pour maintenir les capteurs solaires orientés perpendiculairement au soleil, ce qui permet de capturer davantage d'énergie par rapport à un système à orientation fixe. Il y a deux principaux types de suiveurs (un ou deux axes) qui opèrent en utilisant soit un mécanisme passif ou actif. Bien que les suiveurs sur deux axes permettent de pointer le soleil plus précisément, ils augmentent le coût initial et la complexité du système (Mousazadeh, Keyhani et al., 2009).

De nombreux auteurs ont étudié les systèmes de suivi solaire. Parmi eux, Salah Abdallah (2004) a conçu, construit et étudié quatre systèmes de suivi pour Amman, Jordanie: 1) deux axes, 2) un axe vertical unique, 3) un seul axe est-ouest et 4) un seul axe nord-sud. La production d'énergie par chaque système est supérieure à celle d'un système fixe incliné à 32° de 43,9 % pour un suivi sur deux axes, 37,5 % pour un suivi est-ouest seulement, 34,4 % pour un suivi selon l'axe vertical seulement et 15,7 % pour un suivi nord-sud. Ce test a été fait en continu pendant une journée claire, le 29 mai 2002. Helwa et al. (2000) ont comparé quatre systèmes photovoltaïques: 1) fixe face au sud et incliné à 40° , 2) suivi sur un axe vertical, 3) suivi sur un axe incliné à 6° en direction nord-sud et 4) un suivi sur deux axes. Sur la base d'une année, la comparaison des résultats montre que l'augmentation annuelle du rayonnement recueilli par les systèmes de suivi azimutal, nord-sud et sur deux axe est de 18 %, 11 % et 30 %, respectivement, par rapport au système fixe. Abou-Khader et al. (2008) ont comparé et évalué quatre systèmes: 1) suivi fixe, 2) suivi sur axe vertical, 3) suivi nord-sud, et 4) est-ouest. Des pyranomètres installés sur les panneaux ont mesuré l'irradiation solaire. Les résultats de l'expérience ont montré que le suivi nord-sud était optimal dans ces conditions. Il produisait une puissance de sortie 30-45 % plus élevée que le système fixe incliné à 32° . Koussa et al. (2011) ont mesuré et modélisé des systèmes photovoltaïques avec différents types de suiveurs. Leurs mesures ont eu lieu pendant une période de 18 jours de météo typiques du nord de l'Algérie à une latitude de $36,8^\circ$ (très similaire à celle du Maroc). Le rayonnement direct horaire, le rayonnement global horizontal, le rayonnement diffus et la température ont été mesurés. La production d'électricité pour chaque système - qui dépend de la consommation d'électricité du suiveur, de l'état du ciel, et de la longueur du jour - a été

évaluée. Les résultats obtenus montrent que pendant les jours clairs, le suivi du Soleil est très utile, alors que lors des jours nuageux, il est inutile. Cependant, pendant les jours partiellement nuageux, son utilité est variable en fonction des conditions météorologiques.

A III-2 Description des systèmes photovoltaïques

Deux systèmes similaires PV ont été comparés entre eux, le premier est situé à Montréal, Canada à une latitude $45^{\circ}30'N$ et l'autre système est situé à Casablanca, Maroc à une latitude $33^{\circ}36'N$. Chaque système est composé de 48 modules PV de 300 W pour une puissance totale théorique de 14,4 kW et de 11 kW (net) et quatre onduleurs de 4,4 kW servant à convertir le courant continu en courant alternatif. Ces systèmes sont installés sur deux maisons à toitures inclinées.

Christensen et Barker (2001) ont défini un paramètre (w) comme la différence de latitude et de l'angle d'inclinaison optimale pour panneaux photovoltaïques. Ils ont constaté que w variait de 0° à 16° , avec des valeurs plus élevées dans les latitudes élevées et dans les sites avec un indice annuel de clarté moyenne inférieur. Nous avons fixé la pente à 45° pour le système canadien et à 30° pour le système marocain en raison des latitudes de Montréal et Casablanca. Les deux systèmes sont orientés directement au sud (Yang and Lu, 2007).

A III-3 Simulation

Les simulations ont été réalisées à l'aide du logiciel PVSOL Pro. Ces systèmes ont été analysés sur une base quotidienne, mensuelle et annuelle. La Figure A III-1 montre l'irradiation cumulée (en MWh) sur les panneaux pour chaque mois pendant une période de un an. L'irradiation sur la matrice du système de Casablanca (aire sous la courbe) est de 25,6 % supérieure à celle du système montréalais sur une base annuelle.

Il est à noter qu'en novembre et décembre, le rayonnement solaire est minimum alors que c'est à cette période de l'année que l'on retrouve la pointe de consommation d'électricité (C'est particulièrement vrai à Montréal.). Comme on peut l'observer sur la Figure A III-1 en janvier, février et mars, les deux systèmes reçoivent presque la même quantité de rayonnement. Cela s'explique par le fait qu'à Montréal, pendant près de quatre mois par année, le sol est recouvert de neige. En effet, cette dernière présente un albédo de 0,8 à 0,9 tandis que pour une surface recouverte par de l'asphalte il est de 0,04 à 0,12 et de 0,25 pour une surface d'herbe verte (McEvoy, Markvart et al., 2003).

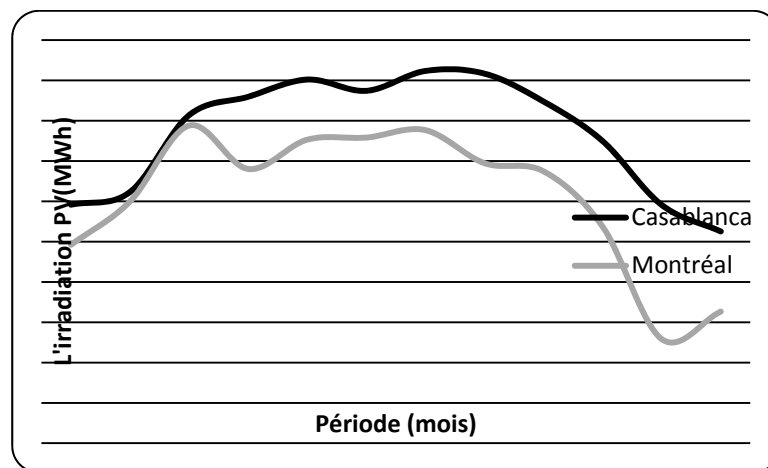


Figure A III-1 Variation annuelle de l'irradiation solaire cumulée sur les systèmes PV en fonction du mois

A III-3.1 Système fixe

La Figure A III-2 montre l'électricité produite (en MWh) chaque année par ces systèmes. Le calcul de cette énergie tient compte de tous les paramètres d'opération notamment de la température de fonctionnement du panneau solaire. De janvier à mars, bien que l'irradiation sur le système de Montréal soit légèrement inférieure à celle du système de Casablanca, la production d'électricité est y similaire voir supérieure. En effet, les basses températures ambiantes augmentent considérablement la production d'électricité à Montréal en hiver par rapport à Casablanca (Brinkworth and Sandberg, 2006). Cependant, cet avantage est moins important le reste de l'année.

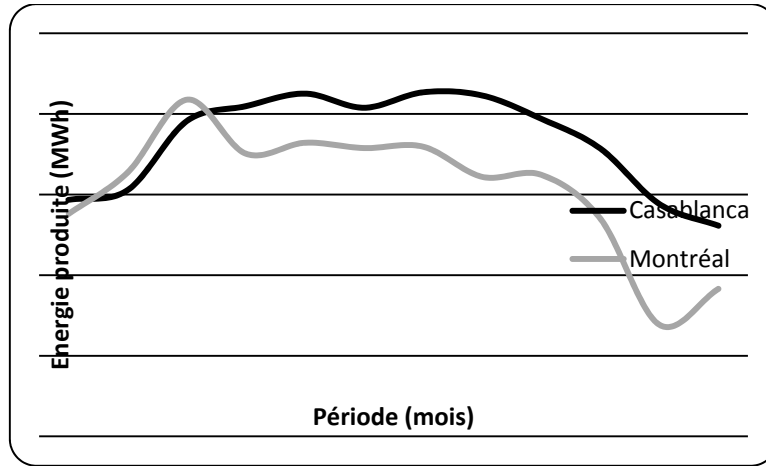


Figure A III-2 Variation annuelle de la production d'électricité des systèmes PV en fonction du mois

En effet, la température moyenne annuelle globale à Montréal est de 7,4 °C, tandis qu'elle est de 18,4 °C à Casablanca. L'équation A III-1 montre la relation entre le rendement électrique du module à la température de fonctionnement, η_C , et le rendement électrique du module à la température de référence, $\eta_{T_{ref}}$ (Skoplaki and Palyvos, 2009).

$$\eta_C = \eta_{T_{ref}} [1 - \beta_{ref}(T_C - T_{ref}) + \gamma \log_{10} G_T] \quad (\text{A III-1})$$

où β_{ref} est le coefficient de température ($\beta_{ref}=0,004 \text{ K}^{-1}$) et γ est le coefficient de rayonnement solaire ($\gamma = 0,12$) du module PV et T_{ref} est de 25 °C. Le terme $\gamma \log_{10} G_T$ est généralement négligé et considéré comme nul (Skoplaki and Palyvos, 2009). La Figure A III-3 montre la température des modules à Casablanca et à Montréal. Il est à noter que c'est la température du panneau solaire qui affecte les performances. Ainsi, la moyenne de la température du module de Montréal est de 16,2 °C alors que celle de Casablanca est de 29,2 °C (Figure A III-3). Ce qui se traduit, en utilisant l'équation A III-1, par un rapport de l'efficacité du module à la température de fonctionnement sur l'efficacité du module à la température de référence, $\eta_C / \eta_{T_{ref}}$, qui varie entre 0,944 et 1,15 pour le système de Montréal et entre 0,936 et 1,044 pour le système de Casablanca.

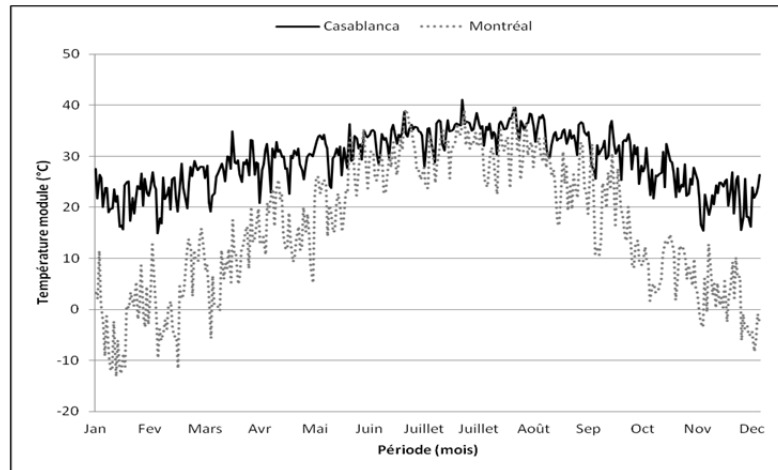


Figure A III-3 Variation annuelle de la température moyenne journalière des systèmes PV

La situation est légèrement différente dans le cas d'un système PV qui suit le Soleil. C'est pourquoi une comparaison a été faite pour ces deux systèmes avec des suiveurs solaires sur deux axes. La figure A III-4 montre l'irradiation cumulée sur les systèmes avec et sans suiveur. Comme on peut l'observer sur cette figure, le système avec suiveur solaire est plus efficace. Dans les deux cas, les suiveurs engendrent près de 30 % d'augmentation de l'irradiation sur les panneaux pour les deux systèmes. On note aussi une réduction sensible de l'irradiation en avril à Montréal, alors que cet effet n'est pas observé à Casablanca. Cela est dû à la fonte de la neige qui réduit l'apport de lumière réfléchi par le sol. L'irradiation baisse ainsi de 13,7 % entre mars et avril pour le système fixe alors qu'elle diminue de 12,8 % pour le système guidé. L'effet est plus grand sur le système fixe, car la proportion de la contribution de la lumière diffusée sur la neige est plus grande par rapport au flux solaire direct en raison du moins bon alignement au départ.

Le suivi solaire présente un avantage supplémentaire dans des conditions météorologiques sévères de Montréal. En effet, au cours d'une nuit d'hiver de grandes quantités de neige peuvent s'accumuler sur les modules photovoltaïques. D'une part, le panneau solaire peut être placé à la verticale pour faire tomber la neige. Même si cette dernière est collée à la surface des panneaux ou si ceux-ci sont recouverts de verglas, le suivi solaire confère un

autre avantage par rapport au panneau fixe. En effet, les panneaux solaires s'échauffent sous l'effet du rayonnement solaire et des pertes par effet Joule dues à la production d'électricité. La plus grande perpendicularité des panneaux équipés d'un système de guidage amplifie ces deux effets. Ainsi, la température de surface du panneau guidé est supérieure de 8 °C à celle du panneau fixe une heure après le lever du Soleil, l'écart se maintenant au cours de la journée. La fonte de la glace en sera d'autant plus rapide.

Cependant, le gain en performance apporté par le système de guidage se fait au prix d'une augmentation de la complexité et des coûts initiaux du système. De plus, l'ajout de moteurs augmente les possibilités de défaillance mécanique, alors que l'absence de composante mobile est considérée comme un des avantages des systèmes solaires. Finalement, l'installation de système de suivi demande plus d'espace, car les panneaux solaires doivent pouvoir se déplacer sans interférer les uns avec les autres.

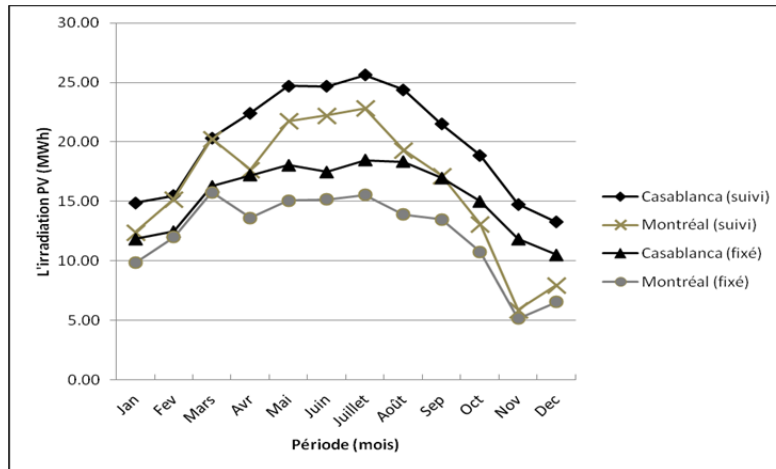


Figure A III-4 Variation de l'irradiation solaire cumulée des deux systèmes PV avec et sans suivi solaire.

A III-4 Synthèse

Les résultats principaux de ces simulations sont présentés au Tableau A III-1. L'analyse montre une irradiation solaire annuelle cumulée supérieure de 25,6 % à Casablanca par

rapport Montréal alors que la production totale d'énergie n'est que de 18,7 % supérieure. Le gain est plus faible pour la production d'énergie, car la corrélation entre l'irradiation et l'efficacité relative du système PV n'est pas linéaire. Par ailleurs, l'effet de la température ambiante sur l'efficacité photovoltaïque n'est pas négligeable. Ainsi, l'efficacité globale du système montréalais est de 0,6 % plus grande que le système installé à Casablanca en raison notamment du climat plus froid. La Figure A III-5 montre la relation entre la température des panneaux PV et leur efficacité. On peut observer qu'une hausse de leur température engendre une baisse de leur efficacité.

Tableau A III-1 Comparaison globale des sites de Montréal et Casablanca

Système	Irradiation annuelle (MWh)	Production d'énergie annuelle (MWh)	Efficacité (%)
Montréal	146,8	18,5	12,5
Casablanca	184,4	21,9	11,9

A III-5 Perspective économique

Une première estimation de la viabilité économique pour Montréal peut être effectuée à l'aide de paramètres simples. Le coût de l'électricité au tarif domestique au Québec est 0,0751 \$/kWh après les 30 premiers kWh. De plus, au tarif domestique, on ne paie pas pour l'appel de puissance maximal et il n'existe pas de tarif préférentiel en fonction de l'heure du jour. La production du système de Montréal représente donc une somme hors taxe de 1390 \$ quel que soit le profil de consommation.

Pour obtenir une viabilité économique basée sur une période de retour sur investissement simple (PRIS ou en anglais ROI) de 5 ans, il faudrait que le système – matériel, installation et entretien compris – coûte (hors taxe) environ 7000 \$. Un système de 14 400 W (théorique) à 0,5 \$/W coûterait environ cette somme. Or, le coût nominal des systèmes PV résidentiels de petite taille dépasse actuellement 5 \$/W ce qui indique que beaucoup de recherche est encore

requis pour rendre économiquement viable cette technologie dans le contexte économique québécois.

Une discussion à cet effet sera intéressante à tenir lors du congrès pour comparer Montréal et Casablanca.

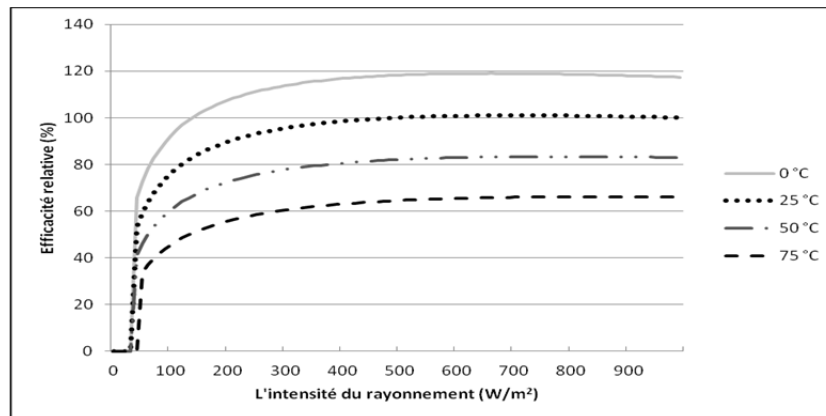


Figure A III-5 Variation de l'efficacité relative des panneaux PV

A III-6 Conclusion

Dans cette étude, deux systèmes PV semblables ont été analysés : l'un exploité dans les conditions climatiques de Montréal au Canada et l'autre dans celles de Casablanca au Maroc. Les résultats des simulations PVSOL Pro montrent que bien que le système de Casablanca produise davantage d'électricité que le système de Montréal, il est moins efficace en raison de la température ambiante en moyenne plus élevée. En janvier et février, bien que le système de Casablanca reçoive plus de rayonnement, le système de Montréal produit davantage d'électricité en raison de la température ambiante plus faible et du rayonnement supplémentaire réfléchi par le sol recouvert de neige.

De plus, l'utilisation de suiveurs sur deux axes pour ces systèmes a été analysée. Les suiveurs entraînent une augmentation annuelle de l'irradiation solaire de 30 % environ par rapport aux

systèmes fixes. En revanche, les traqueurs consomment de l'énergie pour suivre le soleil, augmentent le coût initial et d'entretien, et rendent le système plus complexe. Il resterait donc à pouvoir intégrer ces paramètres à l'analyse afin de voir si au final ce choix s'avère rentable. Enfin, une analyse technico-économique simple a permis de démontrer que pour le Québec, le choix d'installer de tels capteurs ne relève pas de considérations économiques mais plutôt de considérations techniques. En ce sens, en 2012, seuls les endroits dépourvus de connexion au réseau électrique pourraient envisager cette solution de production électrique résidentielle décentralisée.

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ANNEX IV

ÉTUDE DE L'INFLUENCE DE LA NÉBULOSITÉ SUR LA PRODUCTION D'ÉLECTRICITÉ D'UN SYSTÈME PHOTOVOLTAÏQUE AVEC SUIVEUR SOLAIRE FONCTIONNANT AU CANADA (CONFREGE 2012)

Guillermo Quesada^{*}, Daniel Rousse, Yvan Dutil, Mostafa Mehrtash

Chaire de recherche industrielle en technologies de l'énergie et en efficacité énergétique
(T3E), École de technologie supérieure, Montréal, Canada H3C 1K3

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Résumé

Il existe de nombreuses études montrant des gains d'énergie solaire entre 20 et 50 % des systèmes photovoltaïques (PV) avec suiveur solaire par rapport aux systèmes PV fixes. Par contre, des études récentes proposent de fixer l'orientation des modules solaires vers le zénith (position horizontale) lors de conditions complètement nuageuses. Cette approche permettrait de capter plus d'énergie solaire, soit jusqu'à 50 % plus qu'avec un système PV suivant tout simplement le chemin du Soleil.

Ce travail porte sur l'étude de la pertinence de cette dernière proposition pour les systèmes PV avec suiveur solaire fonctionnant au Canada. Une méthodologie basée sur l'utilisation du modèle de ciel isotrope a été utilisée et une analyse d'étude de cas d'un système PV branché au réseau électrique à Toronto a été effectuée.

Mots clés : rayonnement solaire, système photovoltaïque, suiveur solaire.

A IV-1 Introduction

À l'occasion de la conférence Solar Canada 2010 qui s'est tenue les 6 et 7 décembre 2010 à Toronto, la Canadian Solar Industries Association (CanSIA) a publié sa très attendue stratégie pour l'avenir intitulée « Solar Vision 2025 » (CanSIA, 2010). Selon ce document, la capacité solaire photovoltaïque (PV) totale installée au Canada a atteint environ 66 MWp en 2009 et pourrait atteindre entre 9 et 15 GWp d'ici 2025.

C'est dans le cadre de cette conférence que plusieurs entreprises participant activement au programme ontarien « *Micro feed-in tariff program* » se sont réunies. La vedette a été réservée aux systèmes PV avec suiveurs solaires et à leur utilisation potentielle au Canada. De nombreuses études montrant des gains d'énergie solaire entre 20 et 50 % par rapport aux systèmes PV fixes ont été citées (Mousazadeh, Keyhani et al., 2009).

Un système PV avec suiveur solaire peut être défini comme une structure portante qui oriente les panneaux PV vers le Soleil tout au long de la journée. Cette versatilité lui permet de suivre la position qui maximise la quantité de rayonnement solaire incident sur les panneaux PV. Le suivi solaire peut se faire sur deux axes: mouvement azimutal ou horizontal (du lever au coucher du Soleil) et mouvement zénithal ou vertical (selon la hauteur du Soleil pendant la journée).

La stratégie de suivi solaire lors des journées partiellement ou entièrement ensoleillées augmente considérablement la production d'énergie électrique, mais qu'arriverait-il lors des journées complètement nuageuses (ciel complètement couvert)? Des études récentes proposent de fixer l'orientation des modules solaires vers le zénith (position horizontale) lors de conditions complètement nuageuses. Cette approche permettrait de capter plus d'énergie solaire, soit jusqu'à 50 % plus qu'avec un système PV suivant tout simplement le chemin du Soleil.

Kelly et al. (2009) ont effectué des mesures de l'irradiance solaire pendant des périodes nuageuses. Ils ont utilisé six appareils différents pour mesurer l'irradiance solaire sur la position horizontale (H) et sur une surface pointant directement vers le soleil (DTS). Ils ont employé l'expression suivante pour calculer l'avantage de suivi (tracking advantage : TA) d'un suiveur solaire à 2 axes par rapport à un système fixe en position horizontale:

$$TA = \frac{\left(1 - \frac{H}{DTS}\right)}{\left(\frac{H}{DTS}\right)} \quad (A\ IV-1)$$

Parce que toutes les mesures ont été réalisées lors des journées complètement nuageuses, ils ont obtenu une valeur de TA négative (un désavantage de suivi) allant de -0,17 à -0,45 avec une moyenne de -0,31. Ces résultats ont amené à conclure que dans des conditions nuageuses, en particulier pour les journées complètement nuageuses, on capte plus d'énergie solaire en orientant les modules solaires vers le zénith (position horizontale) qu'en suivant tout simplement le parcours du Soleil.

Dans un article ultérieur, Kelly et al. (2011) ont rapporté un vaste ensemble de mesures de l'irradiance solaire à midi. Ils ont employé quatre panneaux photovoltaïques identiques et des pyranomètres associés avec des angles d'inclinaison différents (57°, 42°, 27° et 0°) par rapport à la surface de la Terre. Leur but était de déterminer un algorithme de suivi optimal pour capturer le rayonnement solaire. Les données ont été recueillies à Milford, au Michigan.

Comme dans leur premier travail, ils ont constaté que lors des journées ou périodes complètement nuageuses, un suivi solaire à 2 axes réduit la capture de l'énergie solaire par rapport à un système PV en position horizontale. Ils ont observé que le ratio H/DTS atteint des valeurs de 1,37 pour les journées plus nuageuses. Au cours d'une journée complètement nuageuse, ils ont estimé que l'orientation horizontale d'un panneau PV peut recueillir jusqu'à

50 % plus d'énergie solaire qu'un système qui déplace le panneau PV en direction du Soleil caché derrière les nuages.

En plus de se pencher sur l'effet de l'utilisation de différents mécanismes de suivi solaire sur la performance de systèmes PV, Koussa et al. (2011) ont étudié les principaux paramètres qui influencent la quantité de leur production d'énergie électrique ainsi que celles qui affectent leurs gains par rapport aux traditionnels systèmes PV fixes. À cette fin, les sept configurations suivantes ont été examinées:

OVY: système de suivi solaire avec un simple axe de rotation vertical, où la surface du panneau PV est inclinée selon la pente annuelle optimale

OVS: système de suivi solaire avec un simple axe de rotation vertical (uniaxial), où la surface du panneau est inclinée selon la pente saisonnière optimale

OIY: système de suivi solaire avec un simple axe de rotation incliné (uniaxial), où la surface du panneau PV est inclinée à l'optimum annuel

OIS: système de suivi solaire avec un simple axe de rotation incliné (uniaxial), où la surface du panneau est inclinée selon la pente saisonnière optimale

DT: système de suivi solaire biaxial

FY: panneau fixe et sa surface inclinée selon la pente annuelle optimale

FS: panneau fixe et sa surface inclinée selon la pente saisonnière optimale

Cette étude a été réalisée à partir de mesures horaires du rayonnement solaire direct normal, des rayonnements solaires global et diffus sur le plan horizontal et de la température de l'air. Les données ont été recueillies à Bouzaréah, dans le nord de l'Algérie. Un modèle théorique a été employé pour calculer la performance énergétique d'un système PV fonctionnant selon les configurations mentionnées.

Ils ont également démontré que, pour une journée complètement nuageuse, la position horizontale du panneau PV présente la meilleure performance par rapport au panneau PV fixe et à ceux avec un suiveur solaire uniaxial et biaxiale.

Arriverait-on aux mêmes résultats lors des journées complètement nuageuses pour un système PV avec suiveur solaire fonctionnant au Canada? Cette étude théorique a pour objectif de répondre à cette question. Pour ce faire, on divisera l'étude en deux volets. Dans le premier volet, on étudiera l'énergie solaire disponible, tandis que le deuxième volet s'occupera de la transformation de cette énergie solaire en électricité.

Ce travail propose une méthodologie basée sur l'utilisation du modèle de ciel isotrope. Cette méthodologie permettra d'estimer la valeur théorique du rayonnement solaire global horaire incident sur le plan horizontal sous lequel le système PV en position horizontale reçoit plus d'énergie qu'en suivant le Soleil. Cette valeur sera appelée « rayonnement solaire critique » (I_c).

À la fin, une étude de cas d'un système PV branché au réseau dans la ville de Toronto sera effectuée. La performance du système PV sera simulée avec le logiciel PV-Sol Pro 4.5. Cette simulation aura aussi pour but de valider l'utilisation du modèle de ciel isotrope pour estimer le rayonnement solaire critique.

A IV-2 Méthodologie utilisée pour estimer le rayonnement solaire critique basée sur le modèle de ciel isotrope

Le rayonnement solaire global horaire sur une surface inclinée (I_T) est la somme de ses composantes directe ($I_{T,b}$), diffuse ($I_{T,d}$) et réfléchi au sol ($I_{T,refl}$),

$$I_T = I_{T,b} + I_{T,d} + I_{T,refl} \quad (\text{A IV-2})$$

Pour un ciel nuageux, il est valable d'utiliser le modèle de ciel isotrope pour estimer le rayonnement solaire horaire sur une surface inclinée (I_T) (Hay and McKay, 1985; Reindl, Beckman et al., 1990). Le modèle de ciel isotrope suppose que l'intensité du rayonnement diffus est uniforme sur toute la voûte céleste. Par conséquent, l'incidence du rayonnement

solaire diffus sur une surface inclinée dépend de la fraction de la voûte céleste vue par elle (Noorian, Moradi et al., 2008). Pour le calcul du rayonnement réfléchi au sol incident sur une surface inclinée, on considère l'avant-plan dans le champ de vision de cette surface comme étant un réflecteur diffus et l'horizon dégagé,

$$I_T = I_b \cdot R_b + I_d \cdot R_d + I \cdot R_{refl} \quad (A\ IV-3)$$

I_b : Rayonnement solaire direct horaire sur une surface horizontale (Wh/m^2)

R_b : Facteur géométrique ($R_b \geq 0$). C'est le ratio entre le rayonnement solaire direct sur la surface inclinée ($I_{T,b}$) et le rayonnement solaire direct sur la surface horizontale (I_b),

$$R_b = \frac{\cos \theta}{\cos \theta_z} = \frac{\cos(\phi - \beta) \cdot \cos \delta \cdot \cos \omega + \sin(\phi - \beta) \cdot \sin \delta}{\cos \phi \cdot \cos \delta \cdot \cos \omega + \sin \phi \sin \delta} \quad (A\ IV-4)$$

I_d : Rayonnement solaire diffus horaire sur une surface horizontale (Wh/m^2) R_d : Facteur d'angle de la surface inclinée vers le ciel à tout moment

$$R_d = \left(\frac{1 + \cos \beta}{2} \right) \quad (A\ IV-5)$$

I : Rayonnement solaire global horaire sur une surface horizontale (Wh/m^2). Le rayonnement solaire global horaire sur une surface horizontale (I) est la somme de ses composantes directe (I_b) et diffuse (I_d),

$$I = I_b + I_d \quad (A\ IV-6)$$

R_{refl} : Facteur d'angle de la surface inclinée vers le sol à tout moment

$$R_{\text{refl}} = \rho_g \cdot \left(\frac{1 - \cos \beta}{2} \right) \quad (\text{A IV-7})$$

ρ_g : Coefficient de réflexion au sol

β : Pente du panneau solaire (degré)

θ : Angle d'incidence solaire (degré)

θ_z : Angle zénithal solaire (degré)

φ : Latitude (degré)

δ : Déclinaison solaire (degré).

La déclinaison est calculée à partir de l'équation de Cooper (Duffie and Beckman, 1974)

$$\delta = 23,45 \sin \left(360 \frac{284 + n}{365} \right) \quad (\text{A IV-8})$$

ω : Angle horaire du Soleil (degré)

$$\omega = \frac{180 \cdot (12 - \text{TST})}{12} \quad (\text{A IV-9})$$

n : nième jour de l'année

TST: Heure solaire

Si on introduit la modification de l'expression (6) suivante « $I_b = I - I_d$ » dans l'équation (3), on obtiendra,

$$I_T = (I - I_d) \cdot R_b + I_d \cdot \left(\frac{1 + \cos \beta}{2} \right) + I \cdot \rho_g \cdot \left(\frac{1 - \cos \beta}{2} \right) \quad (\text{A IV-10})$$

En la divisant par « I »,

$$\frac{I_T}{I} = \left(1 - \frac{I_d}{I}\right) \cdot R_b + \frac{I_d}{I} \cdot \left(\frac{1 + \cos\beta}{2}\right) + \rho_g \cdot \left(\frac{1 - \cos\beta}{2}\right) \quad (\text{A IV-11})$$

Le rayonnement solaire critique (I_c) est obtenu lorsque l'équation (A IV-11) est égale à 1. Par conséquent, le rayonnement solaire critique (I_c) sera le rayonnement solaire global horaire incident sur une surface horizontale (I). Sa valeur est égale au rayonnement solaire global horaire incident sur une surface inclinée (I_T).

Puis, selon la condition $I = I_T$, le ratio $\frac{I_d}{I}$ est calculé en utilisant la corrélation suivante,

$$1 = \left(1 - \frac{I_d}{I}\right) \cdot R_b + \frac{I_d}{I} \cdot \left(\frac{1 + \cos\beta}{2}\right) + \rho_g \cdot \left(\frac{1 - \cos\beta}{2}\right) \quad (\text{A IV-12})$$

Pour un système PV suivant le Soleil dans les deux axes,

$$R_b = \frac{1}{\cos\phi \cdot \cos\delta \cdot \cos\omega + \sin\phi \sin\delta} \quad (\text{A IV-13})$$

Orgill et.al. ont présenté une équation de corrélation pour le rayonnement solaire diffus horaire, basée sur des données météorologiques de Toronto sur une période de 4 ans. A partir

de ces données, le ratio $\frac{I_d}{I}$ peut être calculé en fonction de l'indice de clarté horaire « k_t ».

$$\begin{aligned} \frac{I_d}{I} &= 1 - 0,249 \cdot k_t \rightarrow \rightarrow \rightarrow 0 \leq k_t < 0,35 \\ \frac{I_d}{I} &= 1,557 - 1,84 \cdot k_t \rightarrow \rightarrow 0,35 \leq k_t \leq 0,75 \\ \frac{I_d}{I} &= 0,177 \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow k_t > 0,75 \end{aligned} \quad (\text{A IV-14})$$

La plage de $0 \leq k_t < 0,35$ représente des journées complètement nuageuses avec plus de 90% du rayonnement solaire global incident étant diffus. La gamme de $0,35 \leq k_t \leq 0,75$ correspond à des journées partiellement ensoleillées et des journées entièrement ensoleillées sont représentées par $k_t > 0,75$.

En modifiant les corrélations d'Orgill et al. (1977), l'indice de clarté horaire pour les journées complètement nuageuses et partiellement ensoleillées peut être estimé:

$$k_t = \frac{1 - \frac{I_d}{I}}{0,249} \rightarrow \rightarrow \rightarrow \rightarrow \frac{I_d}{I} > 0,91$$

$$k_t = \frac{1,557 - \frac{I_d}{I}}{1,84} \rightarrow \rightarrow 0,177 \leq \frac{I_d}{I} \leq 0,91 \quad (\text{A IV-15})$$

Enfin, le rayonnement solaire critique horaire (I_c) est calculé en utilisant la corrélation suivante,

$$I_c = k_t \cdot I_0 \quad (\text{A IV-16})$$

I_0 : Rayonnement solaire extraterrestre horaire sur une surface horizontale (Wh/m^2). Le rayonnement solaire extraterrestre horaire sur une surface horizontale entre le lever et le coucher du Soleil est donné par (Duffie and Beckman, 1974),

$$I_0 = \frac{12 \cdot G_{sc}}{\pi} \cdot \left[1 + 0,033 \cos \left(\frac{360 \cdot n}{365} \right) \right] \cdot \left[\cos \phi \cdot \cos \delta \cdot (\sin \omega_2 - \sin \omega_1) + \frac{\pi \cdot (\omega_2 - \omega_1)}{180} \cdot \sin \phi \cdot \sin \delta \right] \quad (\text{A IV-17})$$

G_{sc} : Constante solaire = 1353 W/m²

A IV-2.1 Estimation du rayonnement solaire critique

En utilisant la méthodologie décrite ci-dessus, on calculera l'indice de clarté horaire et le rayonnement solaire critique horaire pour un système PV avec suiveur solaire à deux axes. Ce système PV sera situé en Ontario, plus précisément à Toronto (43,67° N et 79,4° O). Le coefficient de réflexion au sol utilisé pour le calcul sera de $\rho_g=0,2$.

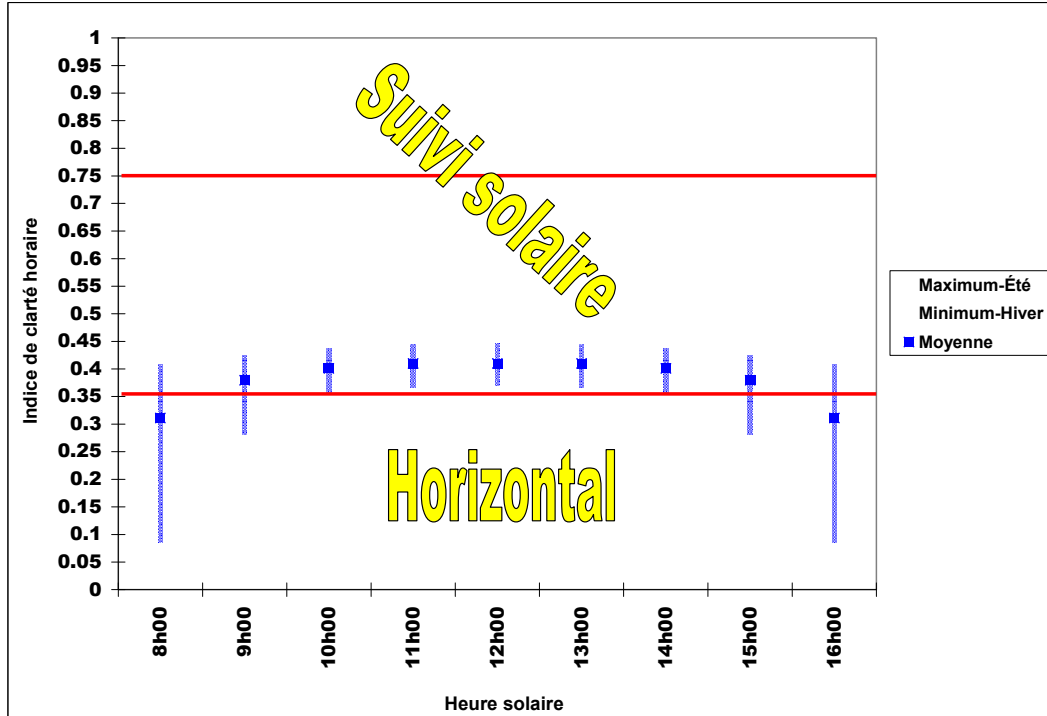


Figure A IV-1 Courbe des indices de clarté horaire calculés avec l'expression

La figure ci-dessus montre que l'indice de clarté calculé se trouve, pour la majorité des heures du jour, proche de l'indice de clarté que dénote un ciel complètement nuageux. Cela confirme le fait que lors des journées complètement nuageuses, le panneau PV reçoit plus d'énergie solaire en restant en position horizontale qu'en suivant le Soleil.

Les figures suivantes illustrent les valeurs du rayonnement solaire critique pour l'été et l'hiver. Il est à espérer que pour des niveaux de rayonnement solaire global incident sur un plan horizontal en dessous de ces valeurs, le système PV recevra plus d'énergie solaire étant en position horizontale. Il est important de préciser que la valeur du rayonnement solaire en Wh/m^2 est valide pour l'heure se terminant au moment indiqué sur l'axe des abscisses.

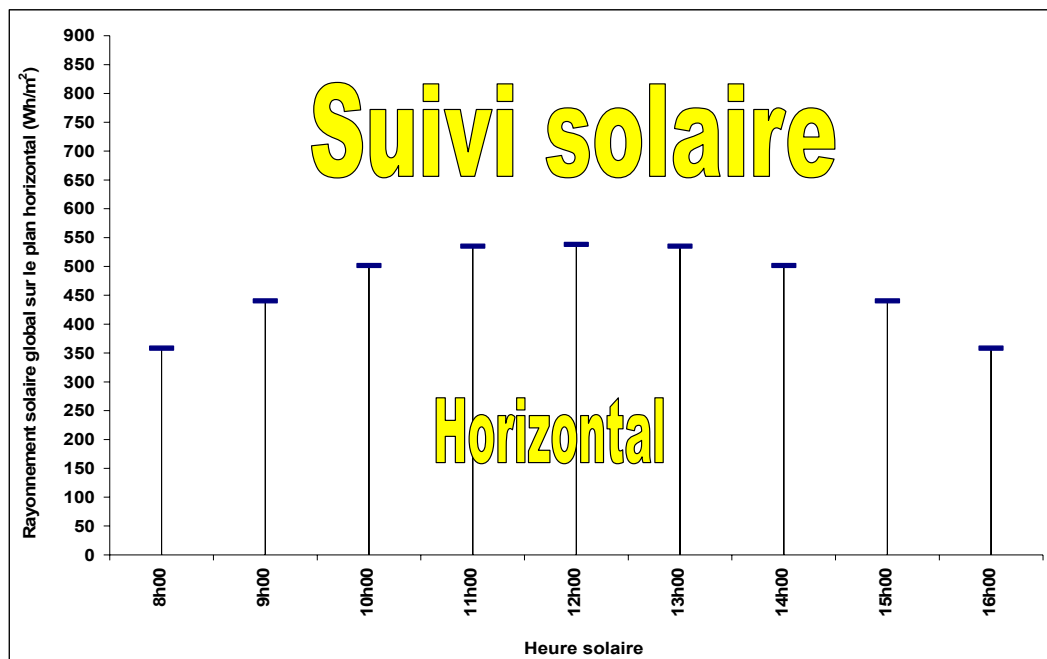


Figure A IV-2 Graphique de rayonnement solaire critique pour Toronto pendant l'été

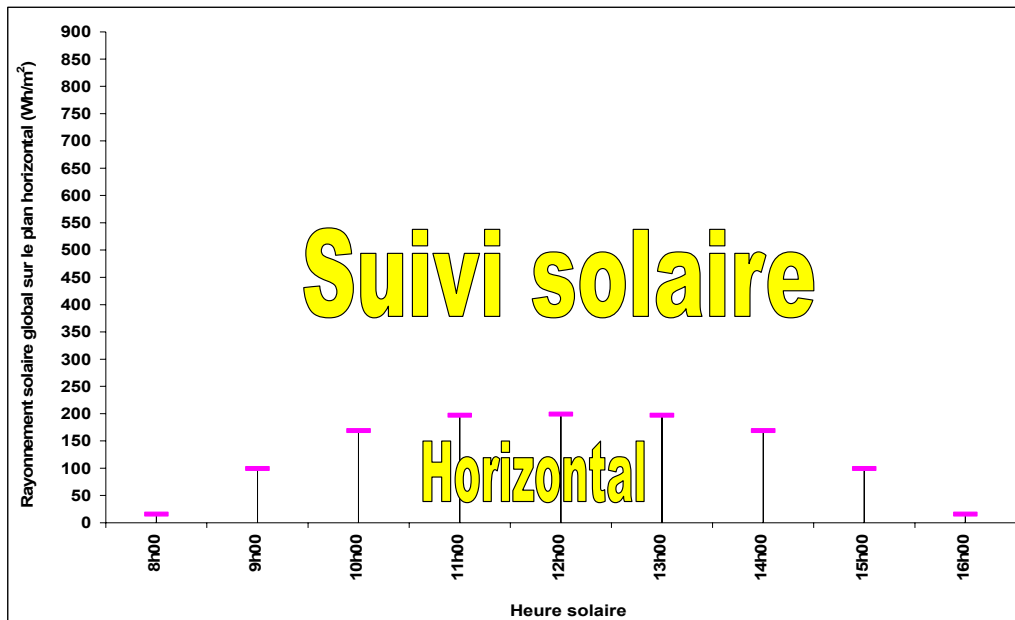


Figure A IV-3 Graphique de rayonnement solaire critique pour Toronto pendant l'hiver

Même si le rayonnement solaire incident sur le plan horizontal lors d'une journée nuageuse est en dessous du rayonnement solaire critique, il reste encore à prouver quantitativement l'avantage de produire de l'électricité fixant les panneaux PV en position horizontale. À niveaux aussi faibles de rayonnement solaire, ce sont les propriétés photosensibles du panneau PV (courbe caractéristique courant-voltage) et les paramètres d'opération des autres composantes du système PV (régulateur, batterie électrique, onduleur) qui peuvent constituer des contraintes considérables à la transformation de l'énergie solaire incidente en énergie électrique. Cet aspect sera abordé dans la section suivante, où le système PV branché au réseau électrique et fonctionnant dans des conditions de ciel complètement nuageux sera étudié.

A IV-3 L'analyse d'études de cas

Pour réaliser cette analyse, le logiciel PV-Sol Pro 4.5 a été utilisé. Il s'agit d'un logiciel de simulation dynamique développé pour la conception et le calcul du rendement de systèmes photovoltaïques branchés au réseau et hors réseau.

Ce logiciel utilise le modèle de ciel anisotrope, proposé par Hay et Davies (Noorian, Moradi et al., 2008), pour estimer le rayonnement solaire horaire incident sur une surface inclinée (I_T). Le modèle de ciel anisotrope divise la voûte céleste en deux zones, une zone pour la partie du ciel autour du Soleil (zone circumsolaire) et l'autre pour la portion du ciel restante. Le rayonnement solaire diffus provenant de la zone circumsolaire est projeté sur la surface inclinée de la même manière que le rayonnement solaire directe. Par conséquent, R_d est la suivante:

$$R_d = \left[(1 - A_i) \cdot \left(\frac{1 + \cos \beta}{2} \right) + A_i \cdot R_b \right] \quad (\text{A IV-18})$$

Ils ont défini un indice anisotrope (A_i) pour pondérer les composantes du rayonnement circumsolaire et isotrope.

$$A_i = \frac{I_b}{I_0} \quad (\text{A IV-19})$$

Dans des conditions de ciel complètement nuageux, la valeur de l'indice anisotrope tend vers zéro et le modèle anisotrope s'approche du modèle isotrope.

Pour effectuer la simulation, un système PV branché au réseau électrique et situé à Toronto a été choisi. Le système a une puissance électrique nominale de 10,8 kW et est composé de 48

panneaux PV de 225 W chacun (Type panneau PV: CS6P-225P) et de 3 onduleurs (Type d'onduleur: Powador 5300). Un schéma de l'installation est présenté dans la figure ci-dessous.

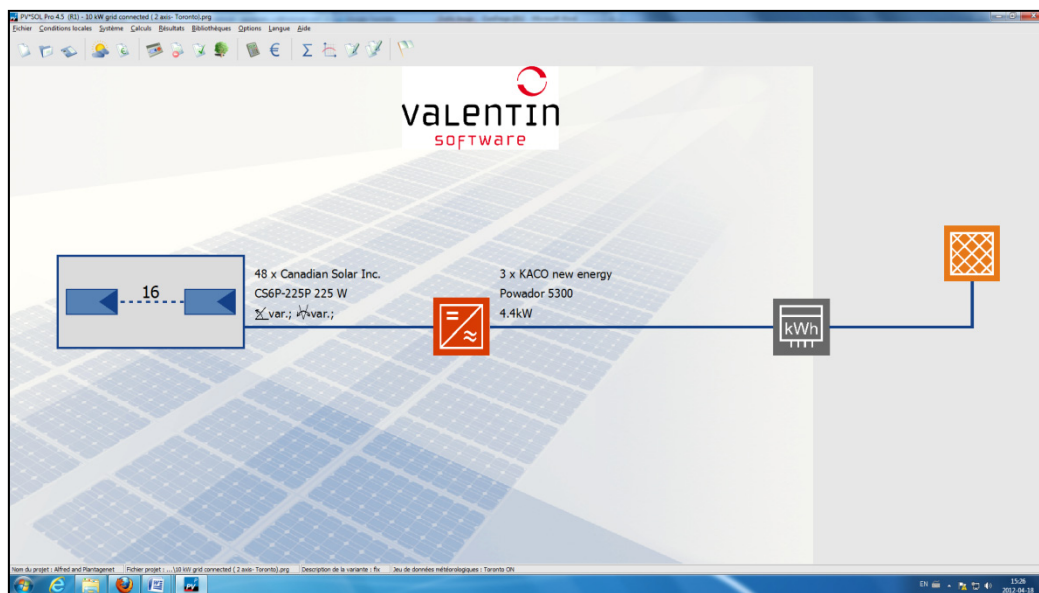


Figure A IV-4 Schéma du système PV branché au réseau électrique

Deux journées complètement nuageuses avoisinant le solstice d'été et d'hiver ont été choisies pour l'analyse.

L'équation (A IV-1) a été utilisée pour comparer l'énergie électrique produite par le système PV en suivant le Soleil (DTS) et en position fixe horizontale (H). Cette équation permet d'estimer l'avantage ($TA > 0$) ou le désavantage ($TA < 0$) du suivi solaire par rapport à un système fixe en position horizontale.

Tableau A IV-1 Journée nuageuse proche du solstice d'été

17 juin				
Heure solaire	I (Wh/m²)	DTS (Wh)	H (Wh)	TA (%)
04:00	0,5	0,0	0,0	0,0
05:00	27,5	0,0	0,0	0,0
06:00	79,9	206,8	389,7	-46,9
07:00	136,0	785,7	971,9	-19,2
08:00	192,5	1265,6	1456,5	-13,1
09:00	234,0	1661,3	1817,0	-8,6
10:00	284,6	2158,1	2263,7	-4,7
11:00	308,3	2417,4	2483,9	-2,7
12:00	307,4	2402,8	2461,4	-2,4
13:00	296,9	2270,1	2353,1	-3,5
14:00	259,6	1895,1	2022,7	-6,3
15:00	221,8	1519,3	1693,9	-10,3
16:00	165,3	1014,3	1208,0	-16,0
17:00	106,9	554,2	714,0	-22,4
18:00	48,3	0,0	59,3	-100,0
19:00	4,0	0,0	0,0	0,0
Valeur totale	2673,4	18150,6	19895,0	

Le Tableau A IV-1 corrobore le fait que pendant des jours complètement nuageux et avec un coefficient de réflexion au sol égal à 0,2, le mécanisme de suivi solaire devrait positionner les panneaux PV dans une position horizontale. Dans cette étude de cas, on produirait 8,8 % moins d'électricité si le système maintient la stratégie de suivi solaire pour une journée

complètement nuageuse. Comme indiqué dans le tableau, cet impact négatif serait plus perceptible dans les heures de lever et coucher du Soleil, en raison de l'inclinaison des panneaux PV (60° à 80°) à ces heures de la journée. Lorsque le système PV se rapproche de la position zénithale, l'effet serait considérablement réduit, puisque les panneaux PV adopteraient une position moins inclinée (entre 20° et 30°). Le comportement décrit ci-dessus est typique d'un suivi solaire au cours de l'été.

Tableau A IV-2 Journée nuageuse proche du solstice d'hiver

26 décembre				
Heure solaire	I (Wh/m²)	DTS (Wh)	H (Wh)	TA (%)
08:00	15,0	0,0	0,0	0,0
09:00	47,2	60,4	169,0	-64,3
10:00	73,1	217,3	413,9	-47,5
11:00	106,9	663,3	857,8	-22,7
12:00	80,6	341,9	595,4	-42,6
13:00	87,3	384,2	655,4	-41,4
14:00	75,8	232,0	424,2	-45,3
15:00	45,3	63,2	81,8	-22,7
16:00	3,7	0,0	0,0	0,0
Valeur totale	534,9	1962,2	3197,4	

Le Tableau A IV-2 montre une accentuation du désavantage du suivi solaire lors des journées complètement nuageuses en hiver. Dans ce cas, on générerait 38,6 % moins d'énergie électrique si le système conservait la stratégie de suivi solaire sous un ciel complètement couvert. Cela pourrait représenter une pénalité importante à la production d'électricité au

cours des journées les plus courtes et de moindre incidence du rayonnement solaire de l'année. Dans les mois d'hiver, l'affectation est à peu près homogène durant toutes les heures de la journée, en raison de la forte inclinaison (60° à 80°) des panneaux PV au cours du suivi solaire.

Ces résultats peuvent être expliqués par le fait que pendant les jours complètement nuageux, il y a une absence quasi totale de rayonnement solaire direct sur le panneau PV. Par conséquent, le rayonnement solaire diffusé par l'atmosphère et celui réfléchi au sol ont une influence importante sur la performance du panneau PV. Néanmoins, pour de faibles valeurs du coefficient de réflexion au sol, le rayonnement solaire diffus domine et son intensité dépend de la fraction de la voûte céleste vue par le panneau PV. Pour cette raison, la position horizontale offrirait la meilleure performance.

En introduisant les valeurs de rayonnement solaire global incident sur le plan horizontal (I) des tableaux 1 et 2 dans les figures 2 et 3, respectivement, on se trouverait dans la région qui recommande disposer les panneaux PV en position horizontale. Ce résultat valide l'utilité de l'usage du modèle de ciel isotrope pour estimer le rayonnement solaire critique.

A IV-4 Conclusions

Au départ, la question suivante se posait: arriverait-on à avoir au Canada la meilleure performance énergétique d'un système PV avec suiveur solaire en disposant le panneau PV en position horizontale lors des journées complètement nuageuses? Pour y répondre, la disponibilité en énergie solaire et la transformation de cette énergie solaire en électricité ont été analysées séparément. La région de Toronto a été sélectionnée pour effectuer cette analyse.

Du côté de la disponibilité en énergie solaire, une méthodologie permettant d'estimer la valeur théorique du rayonnement solaire global horaire incident sur le plan horizontal a été utilisée. La méthodologie en question peut s'employer pour estimer le rayonnement solaire critique dans n'importe quel endroit de l'hémisphère nord. En utilisant cette approche, il a été possible de définir un seuil sous lequel le système PV en position horizontale reçoit plus d'énergie qu'en suivant le Soleil. Cette valeur a été nommée « rayonnement solaire critique ».

Les valeurs obtenues de rayonnement solaire critique se trouvent, pour la majorité des heures du jour, à la proximité du seuil qui sépare la zone des journées partiellement ensoleillées de celles complètement nuageuses. Cela laisse entendre que la performance énergétique d'un système PV avec suiveur solaire serait améliorée en disposant le panneau PV en position horizontale lors des journées complètement nuageuses.

Du côté de la transformation de l'énergie solaire en électricité, l'analyse d'études de cas réaffirme le fait que suivre le Soleil caché derrière les nuages pourrait nuire considérablement à la production d'électricité. Cette affectation serait plus marquée pendant l'hiver.

Cette étude confirme, d'un point de vue théorique, la proposition d'orienter les modules solaires PV vers le zénith pendant des journées avec une nébulosité élevée.

ANNEX V

PERFORMANCE EVALUATION OF SUN TRACKING PHOTOVOLTAIC SYSTEMS IN CANADA (ISME 2012)

Mostafa MEHRTASH¹, Guillermo QUESADA, Yvan DUTIL, Daniel ROUSSE

¹ Chaire de recherche industrielle, École de technologie supérieure, Montréal, Canada
H3C 1K3

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Abstract

This study is performed to investigate the performance of photovoltaic (PV) systems with different types of solar trackers in Northern climates. To this end, four PV systems were simulated; horizontally fixed, inclined fixed, azimuth tracking, and a dual-axis tracking. The simulations have been carried out by use of PVSOL Pro for daily, monthly, and annual periods. The analyses have been done for climate conditions prevailing in Montreal, Canada. Annual analyses show an increase of solar irradiation upon a tilted system, azimuth tracker system, and dual axis tracker system as compared to the horizontal system. This yearly increase is 16.8%, 50.1%, and 55.7% respectively. The results from daily analyses show, as expected, that in clear days the dual axis tracker PV system provides the highest performance, but in overcast conditions all systems perform almost similarly and the optimum position is horizontal. The results indicated that a dual-axis tracking array is the optimum system if it goes to the horizontal position in overcast condition.

Keywords: solar energy, photovoltaic (PV), solar tracking, performance.

A V-1 Introduction

In recent years, energy has become a significant issue in the world. Fossil fuel resources are decreasing while the world energy consumption is increasing considerably. Moreover, the consumption of fossil fuels causes air pollution. An obvious solution for energy problem is utilization of renewable energies like solar, wind, geothermal...etc. Solar energy has the largest potential among all renewable energy resources. Today, solar energy is captured essentially by photovoltaic (PV) modules, solar thermal collectors, solar dryers, solar cookers, and solar water pumps fed by PV. PV modules convert the solar irradiation into electricity and they evolved considerably in recent years.

Solar irradiation impinging on a surface consists in direct, diffused, and reflected radiations. Although the largest fraction of the solar irradiation is direct, both diffuse and reflected radiation must be taken into account for the systems operation analysis. Solar irradiation on PV modules varies with the modules position; the solar irradiation takes its maximum value when the modules are perpendicular to the direct radiation since the main part of solar radiation is direct [1]. The location on earth and local weather conditions are other important parameters in determining solar irradiation amounts. According to the literature, the yearly optimal angle to absorb the maximum amount of solar radiation by fixed PV modules is equal to the local latitude at low latitude locations and up to 14° less than latitude at high latitude areas [2].

Solar trackers are utilized to keep the solar collector surface perpendicular to the Sun and allow collecting a higher amount of solar radiation than with a fixed module. There are two main types of trackers, single axis and dual-axis, which usually operate using either a passive or active mechanism. Although dual-axis trackers follow the sun more precisely, they increase the initial cost and complexity of the system.

Many authors have been studied solar tracking systems. Salah Abdallah [3] designed, constructed and studied four tracking systems for Amman, Jordan: dual-axis, single axis vertical, single axis east-west and single axis north-south. The power generation by each system is greater than that of a fixed system tilted at 32° by 43.9%, 37.5%, 34.4%, and 15.7% for the dual-axis, east-west, vertical, and north-south tracking system, respectively. In [3], the continuous test was made during a day. Helwa et al. [4] compared four PV systems: fixed system facing south and tilted at 40° , vertical axis tracker, tracker with 6° tilted axis (north-south tracker), and dual-axis tracker. The comparison is based on one year measurement of solar irradiation and their power output. The comparison's results show annual increase of collected radiation by azimuth, north-south and dual-axis trackers by 18%, 11% and 30%, respectively, over the fixed system. Abu-Khader et al. [5] compared and evaluated different types of tracking. Four systems have been constructed and studied: fixed, vertical axis tracking, north-south tracking, and east-west tracking. Pyranometers, installed on panels, measured the solar irradiance. Experiments result showed that the north-south tracking was the optimum one. The north-south tracking system produces 30-45% more output power than the fixed system tilted at 32° .

Koussa et al. [6] measured and modeled PV systems with different types of sun trackers. Their measurements were based on 18 typical days and located in north of Algeria with latitude of 36.8° . The hourly direct normal radiation, horizontal global radiation, diffuse radiation, and temperature were measured. Electricity production for each system – that depends on solar tracker electricity consumption, sky state, and day length – was evaluated. The obtained results show that during clear days, tracking the sun is very useful, during cloudy days it is unnecessary, and during partially clear days based on clearness index, it could be unnecessary or useful.

A V-2 Systems descriptions

Four different configurations of PV systems have been studied: horizontally fixed, fixed at the latitude angle, single axis azimuth tracking with tilt angle of 55° , and dual axis tracking PV system. Simulations were made for the situation and weather conditions of Montreal, Canada. Each system consisted of 48 PV modules with the total power of 11.04 kW. Three 4.60 kW inverters have been employed for each system to convert the current from DC to AC form. The first system is kept horizontally to act as a comparison reference. Christensen and Barker [7] defined a parameter (w) as the difference of latitude and optimum tilt angle. They found that w is ranged from 0° to 16° , with higher values in high latitudes and lower annual average clearness index. Therefore, the second system is tilted at 45° since the Montreal's latitude is 45.5° . The third system is an azimuth tracking system which tracks the Sun from east to west with the panels tilted at 55° . This angle is annual optimum, calculated by PVSOL, for azimuth tracking in Montreal. The fourth system is a dual-axis tracking PV array.

A V-3 Simulation

These systems have been analyzed on daily, monthly, and annual bases. Figure A V-1 shows the arrays irradiation over a year. Dual-axis tracking PV array absorbs more radiation than other arrays but it has almost the same performance as azimuth tracking PV array. The irradiation on tilted fixed array is considerably higher than on horizontal fixed array, except in summer since the Sun moves across the sky through a path nearly overhead and a horizontal plane is perpendicular to the direct radiation.

In November and December, we observed the minimum amount of radiation, while the average of electricity consumption arises in winter. Figure A V-2 shows the arrays irradiation for a clear day in winter. As it can be seen from the graph, the dual axis tracker receives more radiation than the others. Figure A V-3 shows arrays irradiation during a clear day in

summer. Here again, the dual-axis tracking system receives more radiation. The azimuth tracking array absorbs almost the same amount of radiation as the dual-axis tracking array, but at noon, when the sun is overhead at the sky, it has the lowest performance since the module is not perpendicular to solar beam radiation. In a clear summer day, the fixed systems also receive almost the same amount of radiation. The efficiency of the PV panels is increased due to a decrease in the ambient temperature.

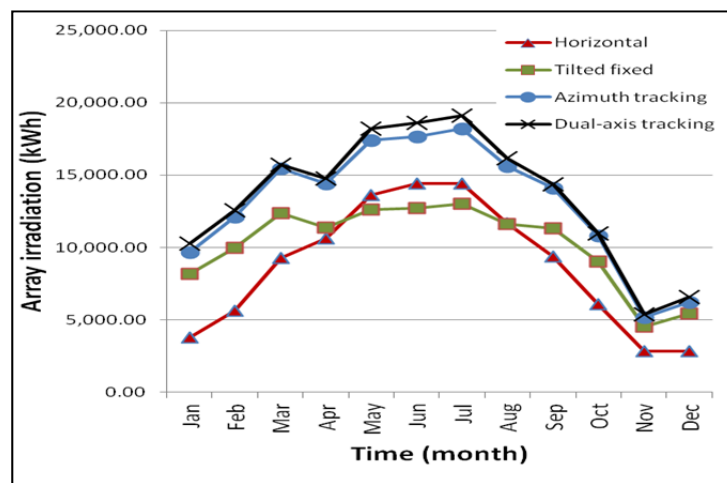


Figure A V-1 Annual array irradiation

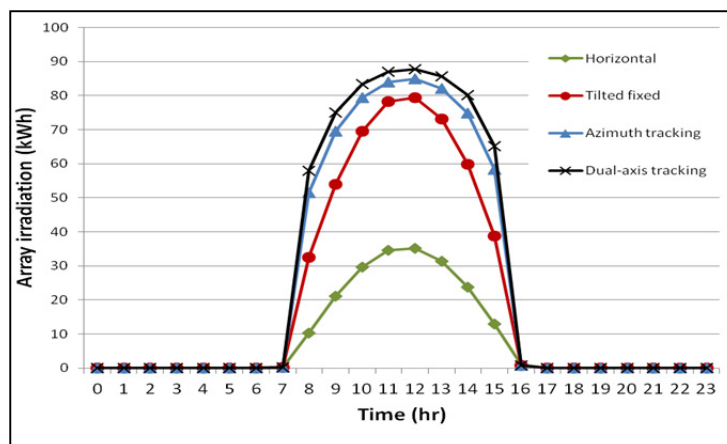


Figure A V-2 Array irradiation in a clear day in winter

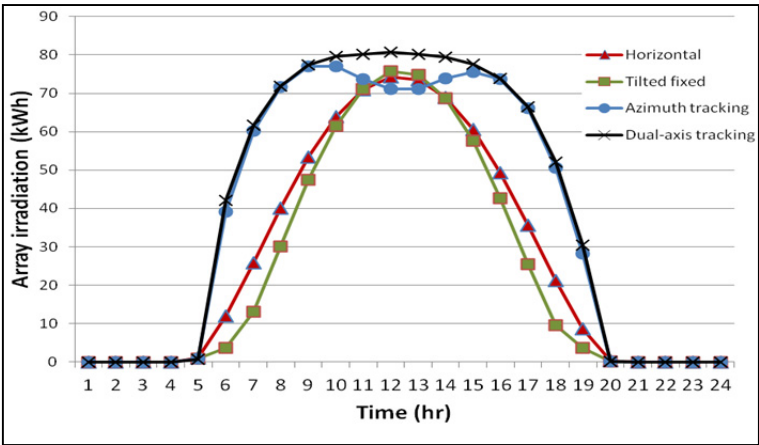


Figure A V-3 Array irradiation on a clear day in summer

Figure A V-4 shows the array irradiation in an overcast day in which the major part of the radiation is diffuse. On a cloudy day, these systems have almost the same performance; however, the horizontal position is optimum.

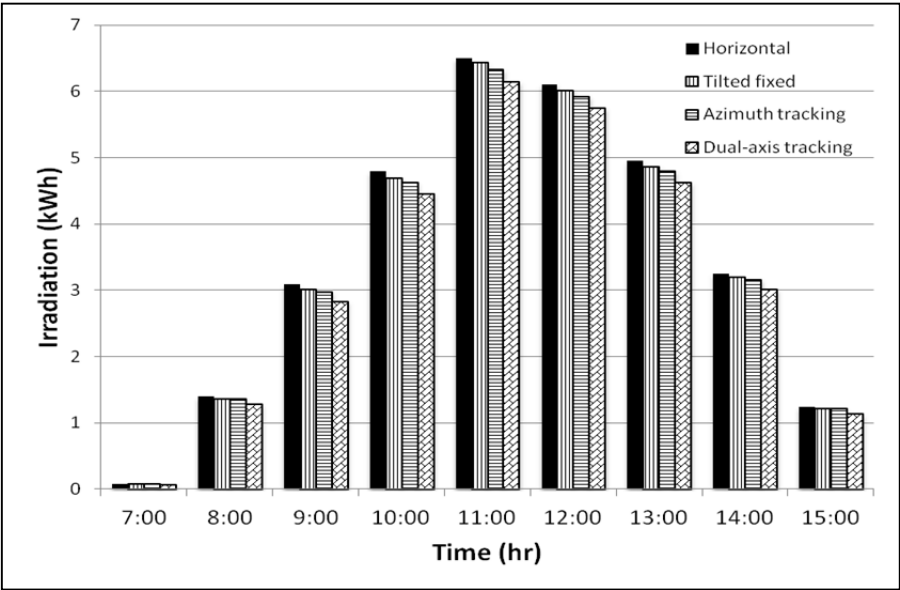


Figure A V-4 Array irradiation on an overcast day

A V-4 Results and discussion

Important results from the simulations are shown in Table A V-1 Annual analysis shows an increase of array irradiation of up to 16.8%, 50.1%, and 55.7% for tilted fixed, azimuth tracking, and dual-axis tracking arrays, respectively, as compared to the horizontal fixed array.

The total energy production of systems as compared to the horizontal array are 23.22%, 65%, and 71% for tilted fixed, azimuth tracking, and dual-axis tracking systems, respectively. The array irradiation percentage increase is not equal to energy production percentage increase since the correlation between irradiation and relative efficiency of the PV system is not linear.

Dual-axis tracking and azimuth tracking array have the highest efficiency among these systems. The annual efficiencies of fixed arrays are 11% and 11.7% for horizontal and tilted fixed arrays, respectively, while the azimuth and dual-axis tracking systems have the same efficiency of 12.2%.

In Figure A V-5, these systems compared in three different typical days. In clear days, both in summer and winter, the highest irradiation belongs to the dual-axis tracking. On an overcast day, all the systems receive almost the same amount of irradiation approximately, but the horizontal position is the optimum angle for these conditions.

In Figure A V-5, arrays irradiances for three typical days are shown. On an overcast day, the irradiation is obviously shown to be very low as compared to clear day's irradiation. Finally, according to all analyses, the dual-axis tracking array has the highest performance among the investigated systems. The optimum strategy for tracking the sun is to use a dual-axis tracker in clear conditions and to move to the horizontal position when the weather is overcast. Although the dual-axis tracking system has the highest performance, it increases the initial

cost, complexity of the system, and the maintenance cost. Furthermore, the azimuth tracking provides 94% of the energy production of dual-axis tracking array, while it is cheaper and simpler to implement [5].

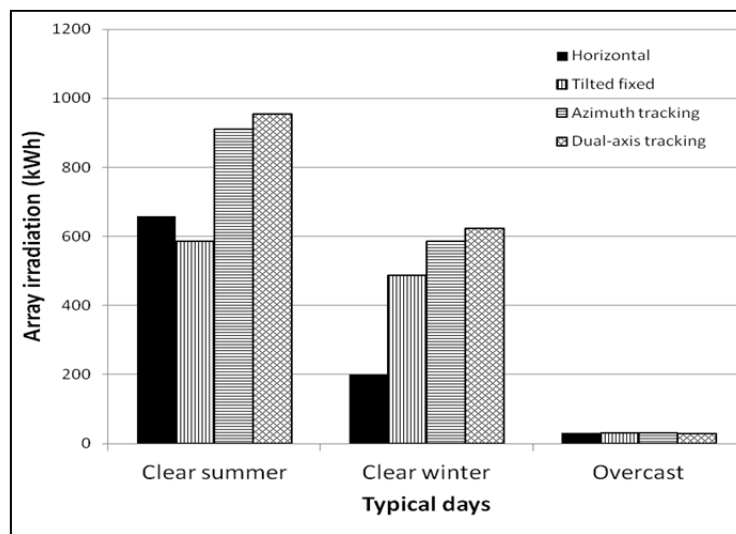


Figure A V-5 Array irradiancies in different typical days

A V-5 Conclusion

In this study four different PV arrays were analyzed: horizontal, fixed tilted, azimuth tracking, and dual-axis tracking. These are operating under climate conditions of Montreal, Canada. The results of the PV Solve Pro simulations show that the dual-axis tracking array provides the best performance. It receives 55.7% more solar radiation and generates 71% more electricity than the horizontal system over a year. Although the azimuth tracking system receives less solar radiation and generates less electricity than the dual-axis tracking array, it has the same average efficiency.

Table A V-1 Overall comparison

Array	Annual irradiation (MWh)	Energy production (MWh)	Efficiency (%)	Cloudy day irradiation (kWh)	A Clear winter day irradiation (kWh)	A Clear summer day irradiation (kWh)
Horizontal fixed	104.5	11.6	11	31.4	200.6	659
Tilted fixed	122.1	14.3	11.7	30.8	486.4	586
Azimuth tracking	156.9	19.1	12.2	30.4	585.7	910
Dual-axis tracking	162.7	19.9	12.2	29.3	623.8	954

Furthermore, the azimuth trackers are single axis and therefore much cheaper and simpler than dual-axis trackers. The dual-axis tracking system receives only 3.7% more solar radiation and produces only 4% more electricity than the azimuth tracking array. The consumption of the trackers is proportional to the tracking accuracy. While tracking the Sun is useful in clear days, it is counterproductive in overcast days. Consequently, the optimum method of sun tracking is using dual-axis tracker to follow the sun completely in clear sky conditions and go to the horizontal position in overcast conditions. These results are supported by previous studies [8].

The upcoming work will be experimental as a dual-axis tracking system has been installed in Hawkesbury, Ontario. This array will be monitored during winter 2012 to investigate its behavior in the drizzle, snow, and ice conditions.

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